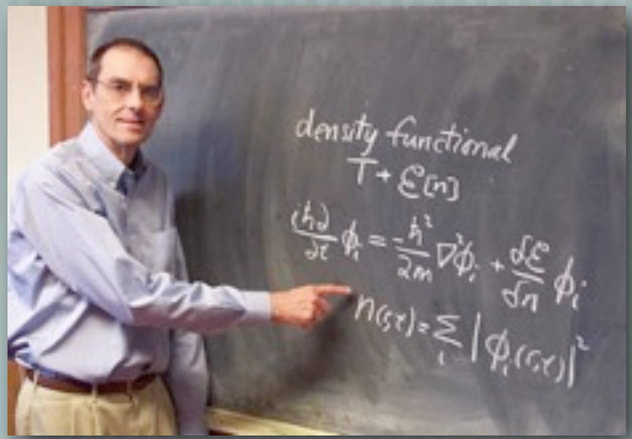
Photons from Relativistic Heavy Ion Collisions: Progress and Puzzles



BertschFest

Outline

- Sources & EM emissivity: Rates
- Modelling the evolving system:
  - 3D hydro
  - 3D viscous hydro
  - Fluctuating initial states
- How are the photon yields dependent on the dynamics?
- Is it the same for dileptons?
- Status of our understanding of the data

Charles Gale
McGill University

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1. **Hard photons in proton-nucleus collisions.**
K. Nakayama (Julich, Forschungszentrum), G.F. Bertsch (Michigan State U., NSCL). Dec 1989. 6 pp.
Published in **Phys.Rev. C40 (1989) 2520-2526**
DOI: 10.1103/PhysRevC.40.2520
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Journal Server: Phys. Rev. C Server
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2. **Potential model calculation of energetic photon production from heavy ion collisions.**
K. Nakayama (Julich, Forschungszentrum & Georgia U.), G.F. Bertsch (Michigan State U., NSCL). Aug 1989. 6 pp.
Published in **Phys.Rev. C40 (1989) 685-691**
DOI: 10.1103/PhysRevC.40.685
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Journal Server: Phys. Rev. C Server
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3. **Production Of Energetic Photons Via Excitation Of The Delta Resonance In Heavy Ion Collisions.**
W. Bauer, G.F. Bertsch (Michigan State U.). 1989.
Published in **Phys.Lett. B229 (1989) 16-19**
DOI: 10.1016/0370-2693(89)90146-9
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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Detailed record - Cited by 3 records

4. **Ultradipole photons in low-energy heavy-ion reactions.**
K. Nakayama, G.F. Bertsch (Michigan State U.). Nov 1987. 4 pp.
Published in **Phys.Rev. C36 (1987) 1848-1852**
DOI: 10.1103/PhysRevC.36.1848
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Journal Server: Phys. Rev. C Server
Detailed record - Cited by 9 records

5. **High energy photon production in nuclear collisions.**
K. Nakayama, G. Bertsch (Michigan State U., NSCL). Dec 1986. 10 pp.
Published in **Phys.Rev. C34 (1986) 2190-2200**
DOI: 10.1103/PhysRevC.34.2190
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Journal Server: Phys. Rev. C Server
Detailed record - Cited by 29 records

6. **Energetic photons from intermediate energy proton- and heavy-ion-induced reactions.**
W. Bauer, G.F. Bertsch, Wolfgang Cassing, Ulrich Mosel (Michigan State U., NSCL & Giessen U.). Dec 1986. 6 pp.
Published in **Phys.Rev. C34 (1986) 2127-2133**
DOI: 10.1103/PhysRevC.34.2127
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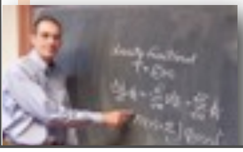
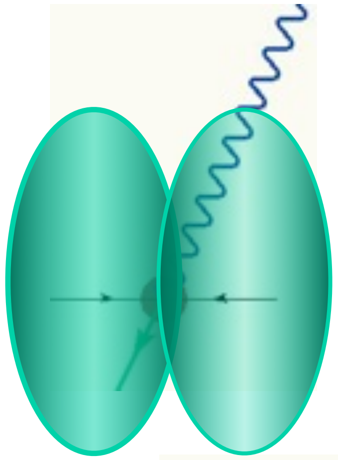
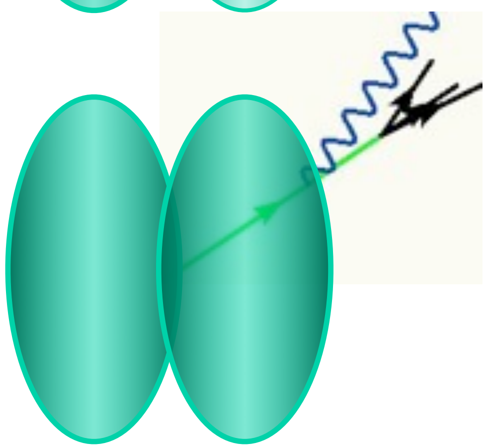


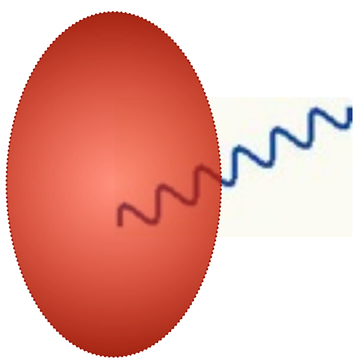
Sources of photons in a relativistic nuclear collision:



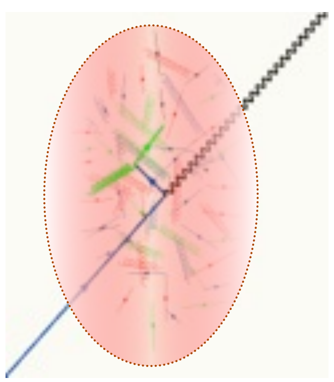
Hard direct photons. pQCD with shadowing
Non-thermal



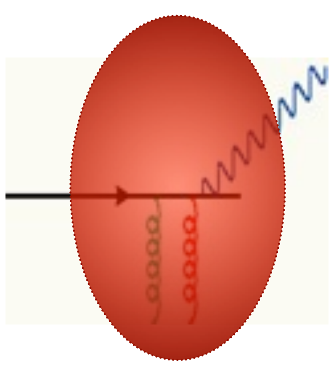
Fragmentation photons. pQCD with shadowing
Non-thermal



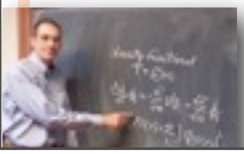
Thermal photons
Thermal



Jet-plasma photons
Thermal



Jet in-medium bremsstrahlung
Thermal



Info Carried by the Radiation

$$dR = -\frac{g^{\mu\nu}}{2\omega}\frac{d^3k}{(2\pi)^3}\frac{1}{Z}\sum_i e^{-\beta K_i}\sum_f (2\pi)^4\delta(p_i - p_f - k)$$
$$\times \langle j \,|\, J_\mu \,|\, i\rangle\langle i \,|\, J_\nu \,|\, j\rangle$$

Thermal ensemble average of the current-current correlator

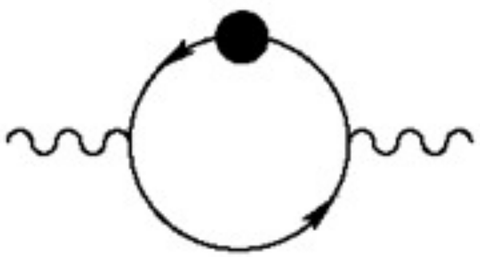
Emission rates:

$$\omega\frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3}\mathrm{Im}\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \qquad \text{(photons)}$$

$$E_+E_-\frac{d^6R}{d^3p_+d^3p_-} = \frac{2e^2}{(2\pi)^6}\frac{1}{k^4}L^{\mu\nu}\,\mathrm{Im}\,\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \qquad \text{(dileptons)}$$

McLerran, Toimela (85), Weldon (90), Gale, Kapusta (91)

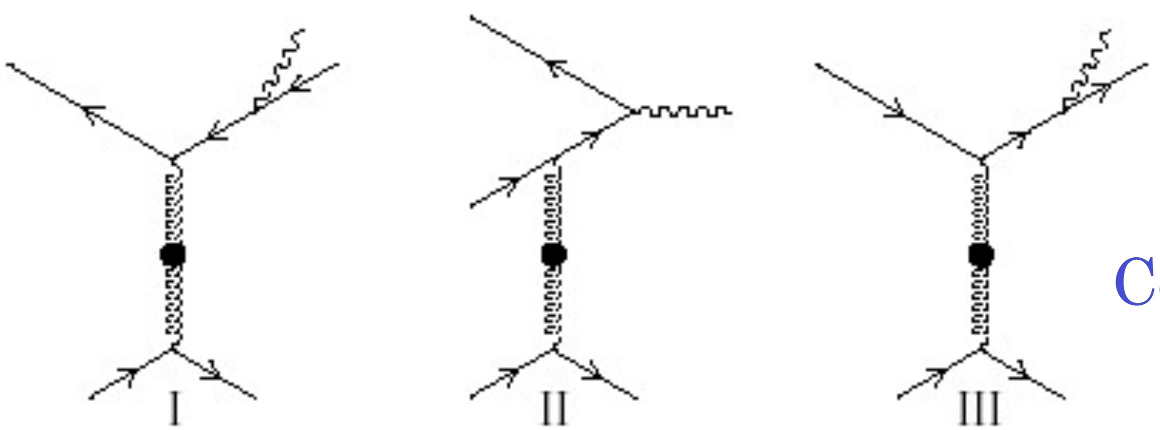
Thermal Photons from hot QCD: HTL program (Klimov (1981), Weldon (1982), Braaten & Pisarski (1990); Frenkel & Taylor (1990))



$$\mathrm{Im}\,\Pi^{\mu}_{R\mu} \sim \ln\left(\frac{\varpi T}{\left(m_{th}(\sim gT)\right)^2}\right)$$

Kapusta, Lichard, Seibert (1991)
Baier, Nakkagawa, Niegawa, Redlich (1992)

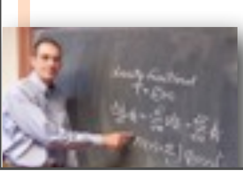
Going to two loops: Aurenche, Kobes, Gelis, Petitgirard (1996)
Aurenche, Gelis, Kobes, Zaraket (1998)



Co-linear singularities: $\alpha_s^2\left(\frac{T^2}{m_{th}^2}\right) \sim \alpha_s$

2001: Results complete at $O(\alpha_s)$

Arnold, Moore, and Yaffe JHEP **12**, 009 (2001); JHEP **11**, 057 (2001)
Incorporate LPM; Inclusive treatment of collinear enhancement, photon and gluon emission

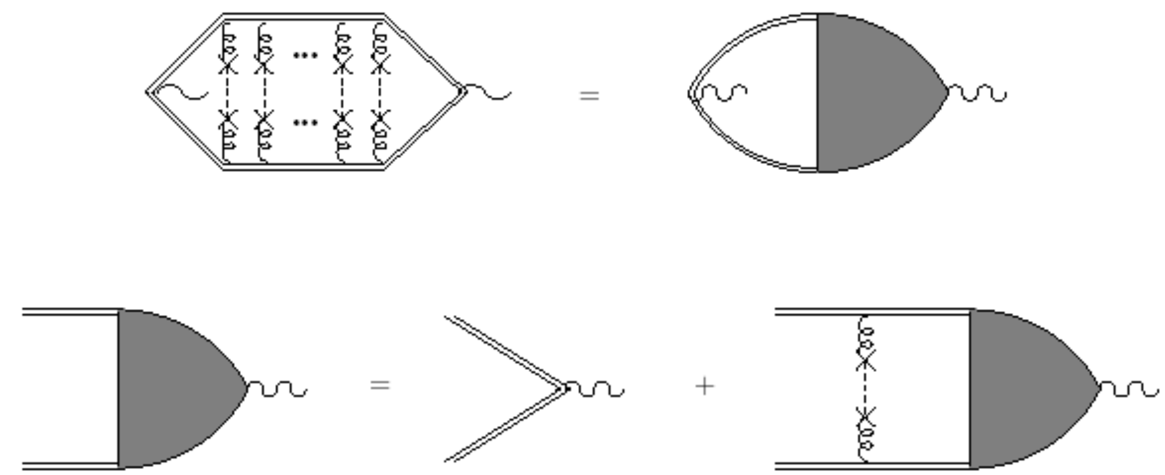


Are these rates final?

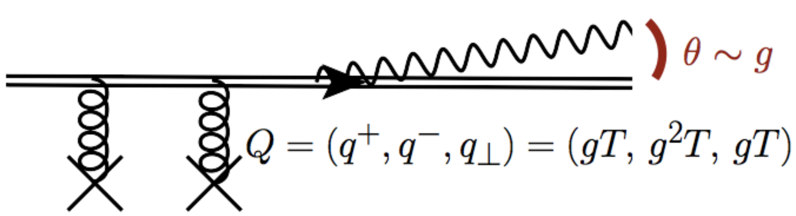
- Approach is LO, but

$$\alpha_s \sim 0.2 - 0.3$$

- Integral equation can be written in terms of a single-gluon scattering kernel:



NLO:

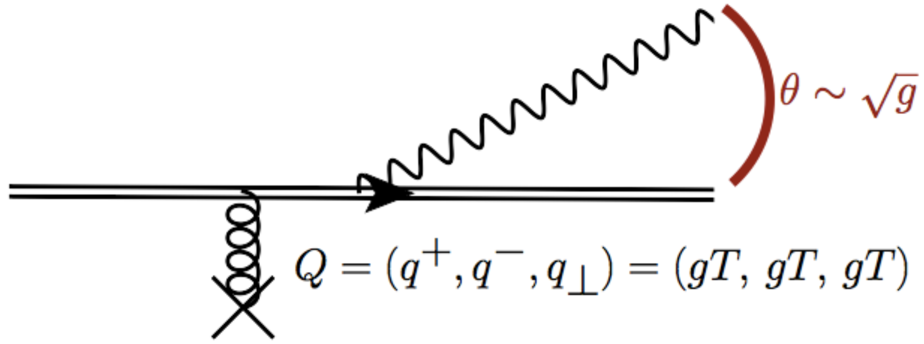


$$C(q_T)_{\rm LO} = \frac{Tg^2 m_D}{q_T(q_T + m_D)} \Rightarrow \text{NLO}$$

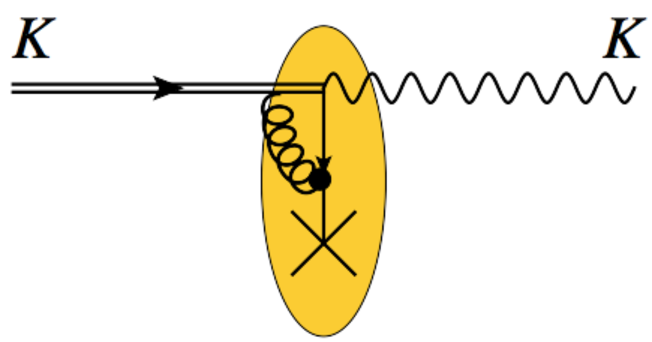
Aurenche, Gélis, Zaraket (2002)

Simon Caron-Huot PRD (2010)

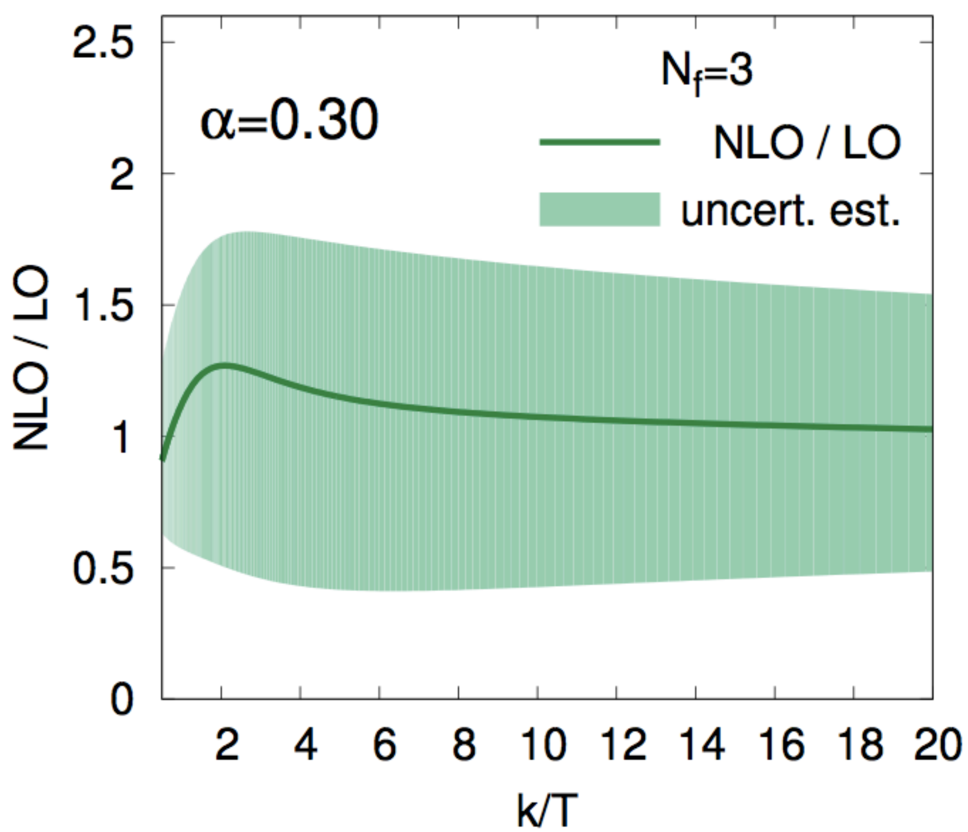
Larger angle emission



Conversion photons



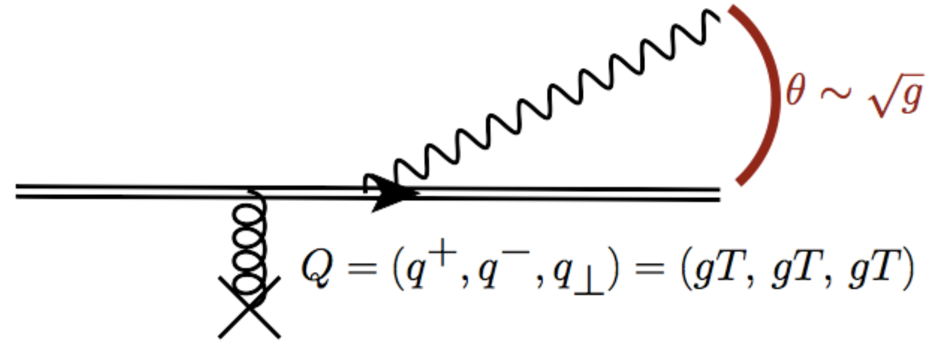
$$R_{\mathrm{NLO}} \sim g^3 \ln(1/g) + g^3$$



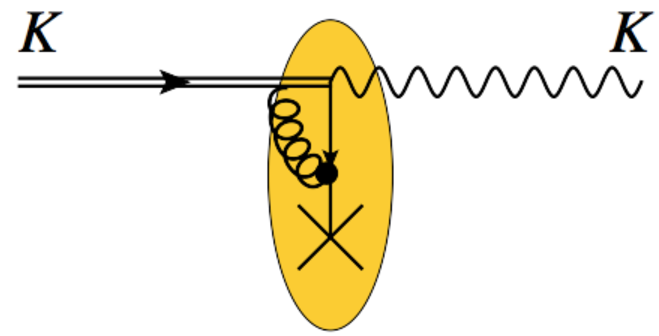
- Net correction to emission rate not numerically important in region up to k/T ~10
- Techniques developed here will have other applications in FTFT

J.Ghiglieri,J.Hong,A.Kurkela,E.Lu,G.D.Moore,D.Teaney (2012)

Larger angle emission

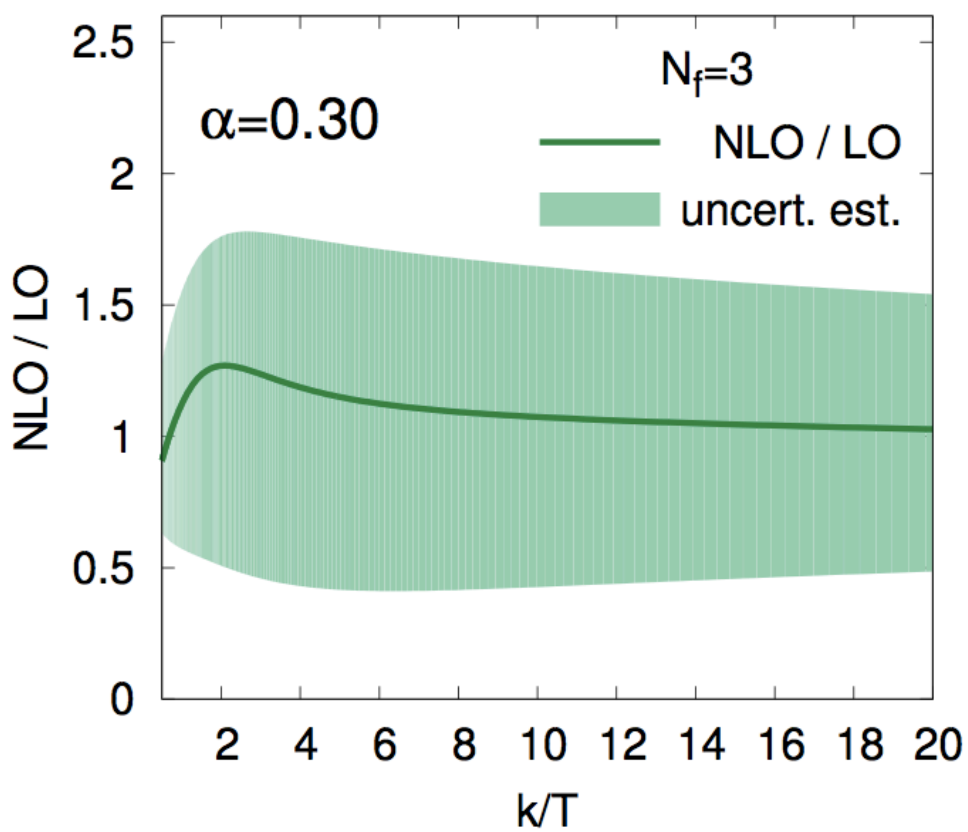


Conversion photons



$$R_{\mathrm{NLO}} \sim g^3 \ln(1/g) + g^3$$

PROGRESS



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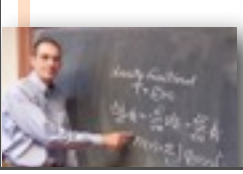


Chiral, Massive Yang-Mills:

O. Kaymakcalan, S. Rajeev, J. Schechter, PRD 30, 594 (1984)

$$\mathcal{L} = \frac{1}{8} F_\pi^2 \,\mathrm{Tr}\, D_\mu U D^\mu U^\dagger + \frac{1}{8} F_\pi^2 \,\mathrm{Tr}\, \mathrm{M}\left(\mathrm{U} + \mathrm{U}^\dagger\right)$$

$$- \frac{1}{2} \mathrm{Tr}\left(F_{\mu\nu}^{L} F^{L\mu\nu} + F_{\mu\nu}^{R} F^{R\mu\nu}\right) + m_0^2 \mathrm{Tr}\left(A_\mu^{\mathrm{L}} A^{L\mu} + A_\mu^{R} A^{R\mu}\right)$$

$$+ \text{ non-minimal terms}$$

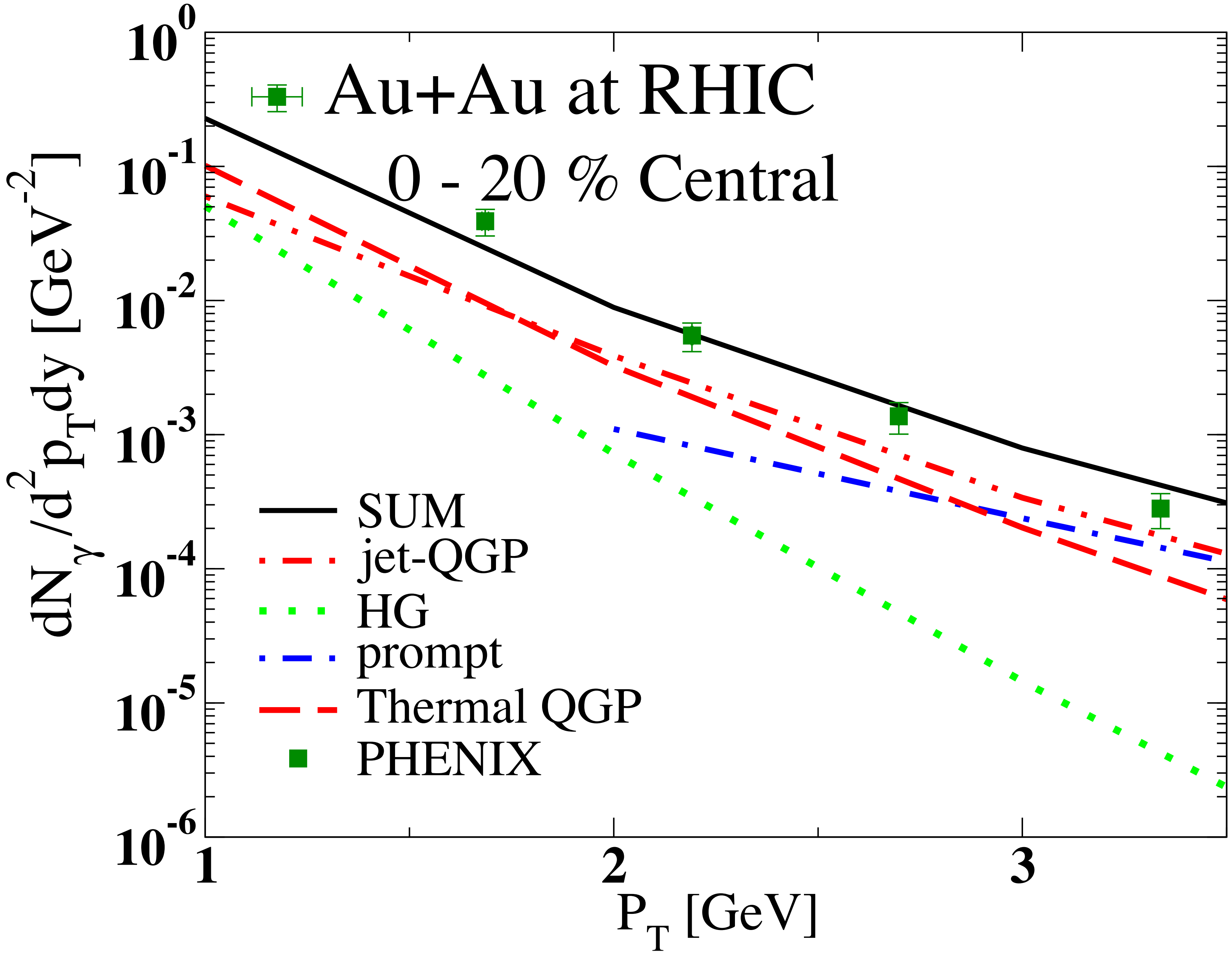
Parameters and form factors are constrained by hadronic phenomenology:

- Masses & strong decay widths
- Electromagnetic decay widths
- Other hadronic observables:
  - *e.g.* $a_1 \rightarrow \pi \rho \quad D/S$

(See also, Lichard and Vojik, Nucl. Phys. (2010); Lichard and Juran, PRD (2008))

EM emissivities computed: Turbide, Rapp, Gale, PRC (2004); Turbide, McGill PhD (2006)

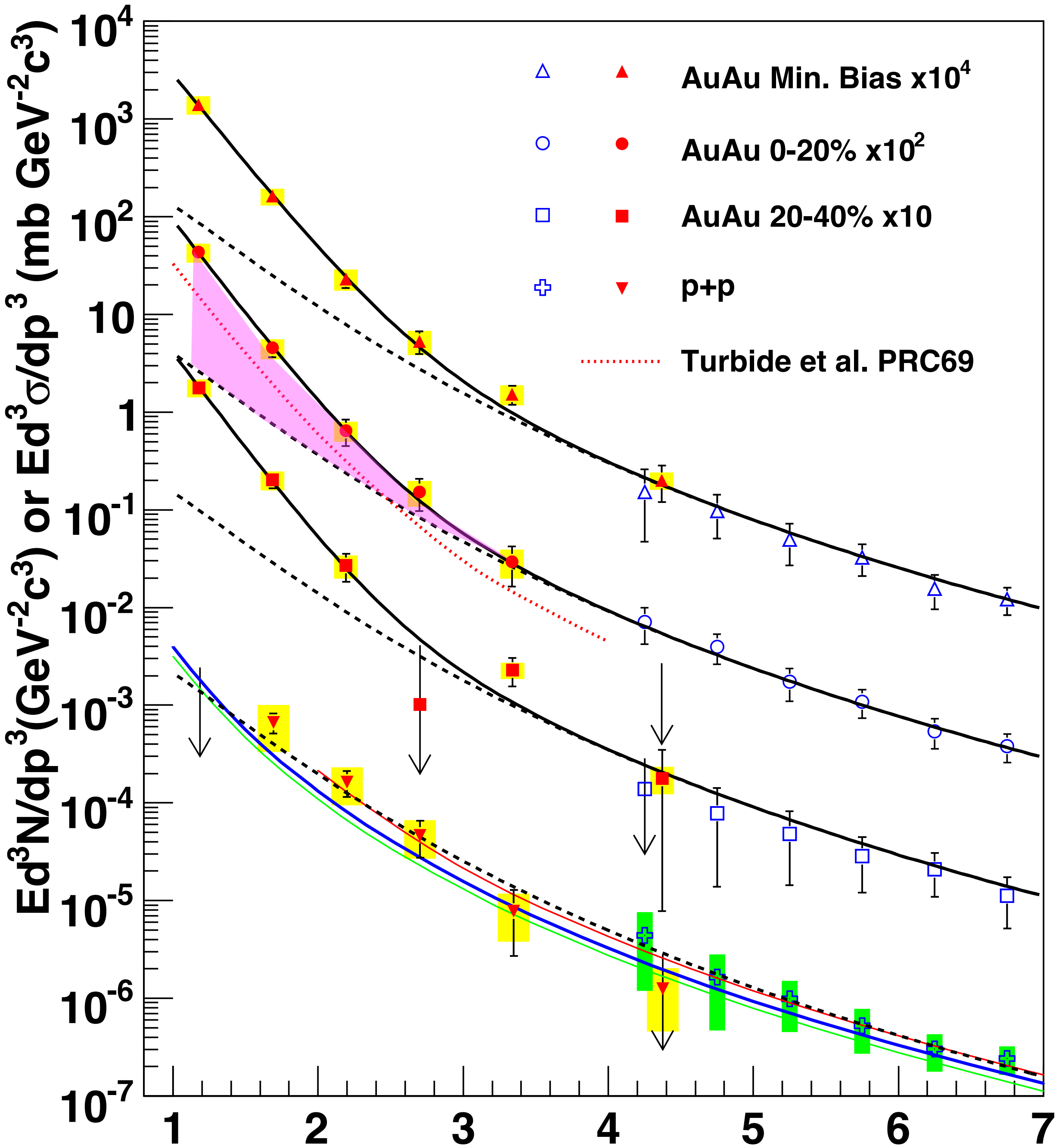
Applying this to interpret photons measured @ RHIC: Rates are integrated using relativistic hydrodynamic modeling



- At low p_T, spectrum dominated by thermal components (HG, QGP)
- At high p_T, spectrum dominated by pQCD
- Window for jet-QPG contributions at mid-p_T

Turbide, Gale, Frodermann, Heinz, PRC (2008);
Higher p_T: G. Qin et al., PRC (2009)

One of the uses of photons: Characterizing the hot matter created at RHIC



PHENIX, PRL 104 (2010)

$$T_{\text{excess}} = 221 \pm 19 \pm 19\,\text{MeV}$$

Charles Gale

Saturday, 8 September, 12

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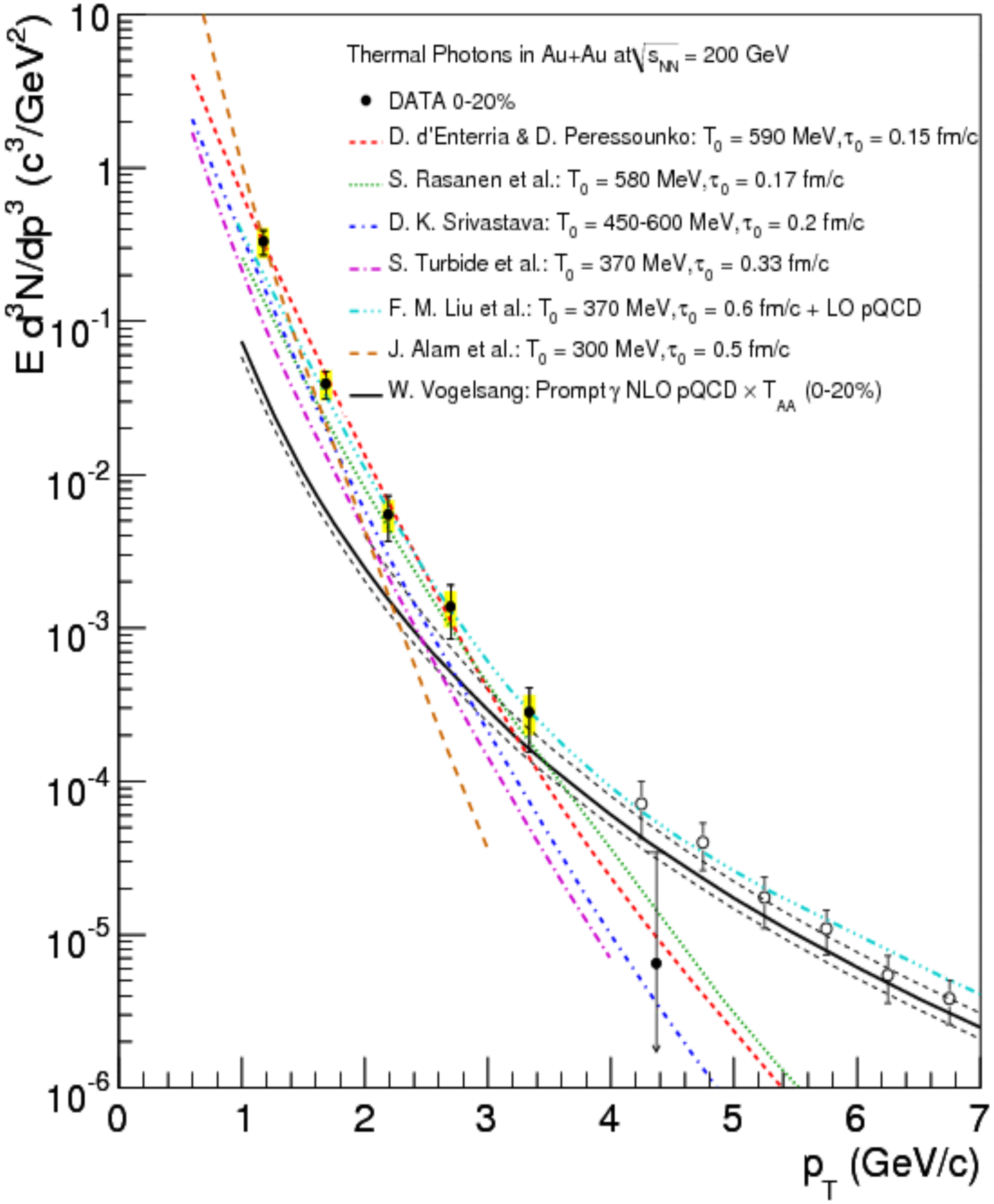

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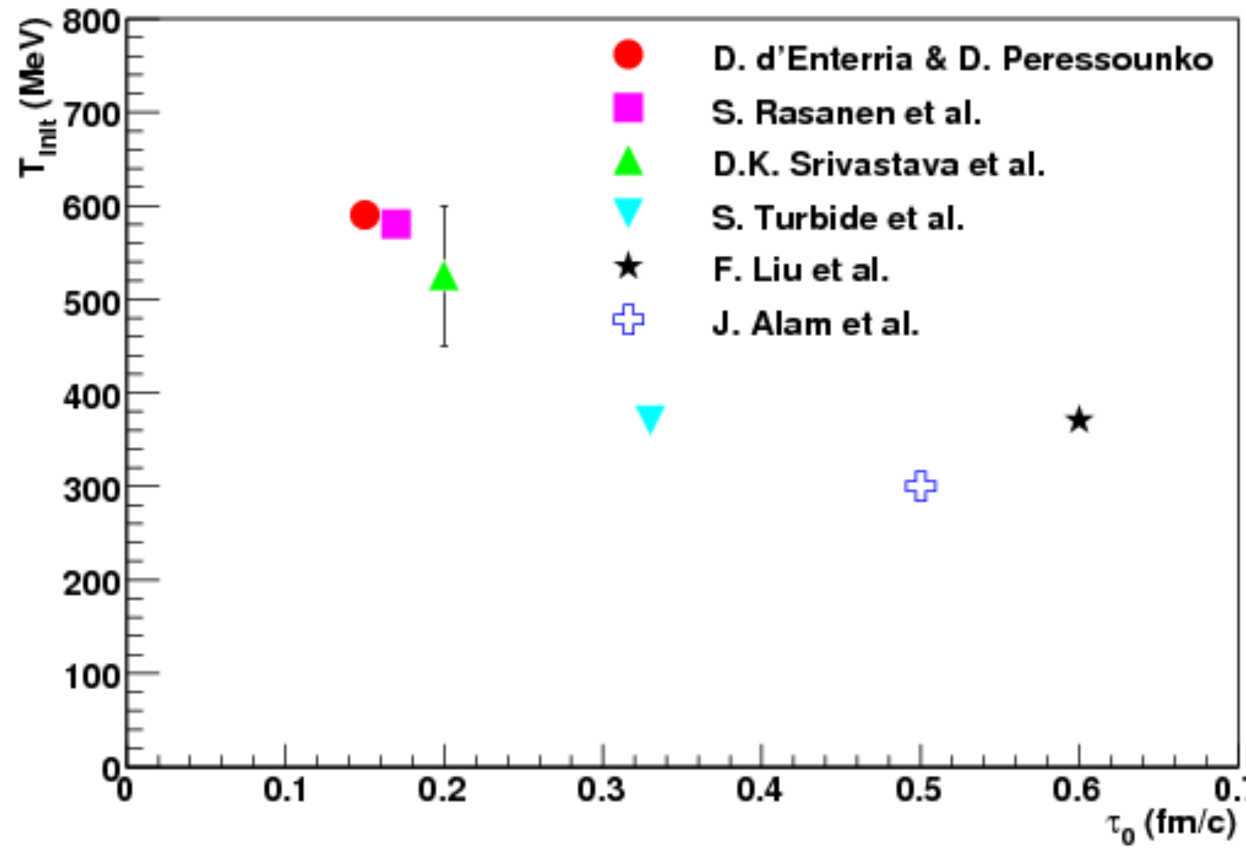


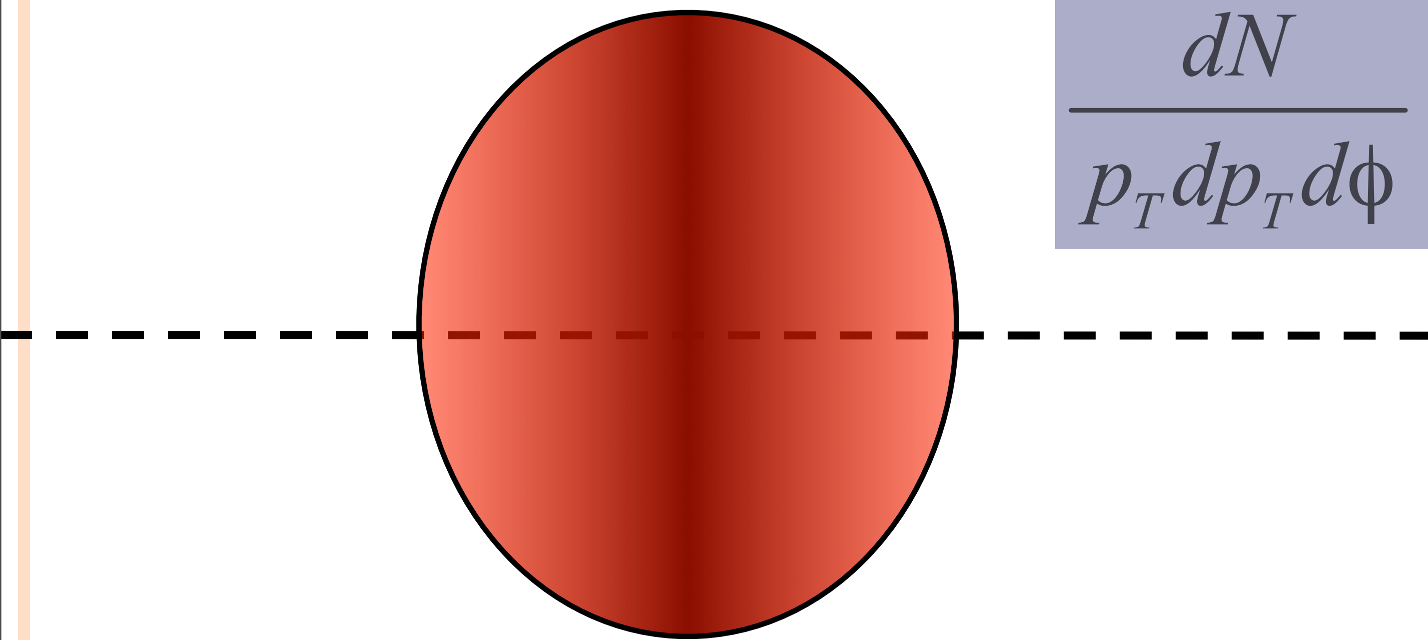
T_{ini} = 300 to 600 MeV
t_0 = 0.15 to 0.5 fm/c

D'Enteria & Peressounko, Eur. Phys. J. (2006)

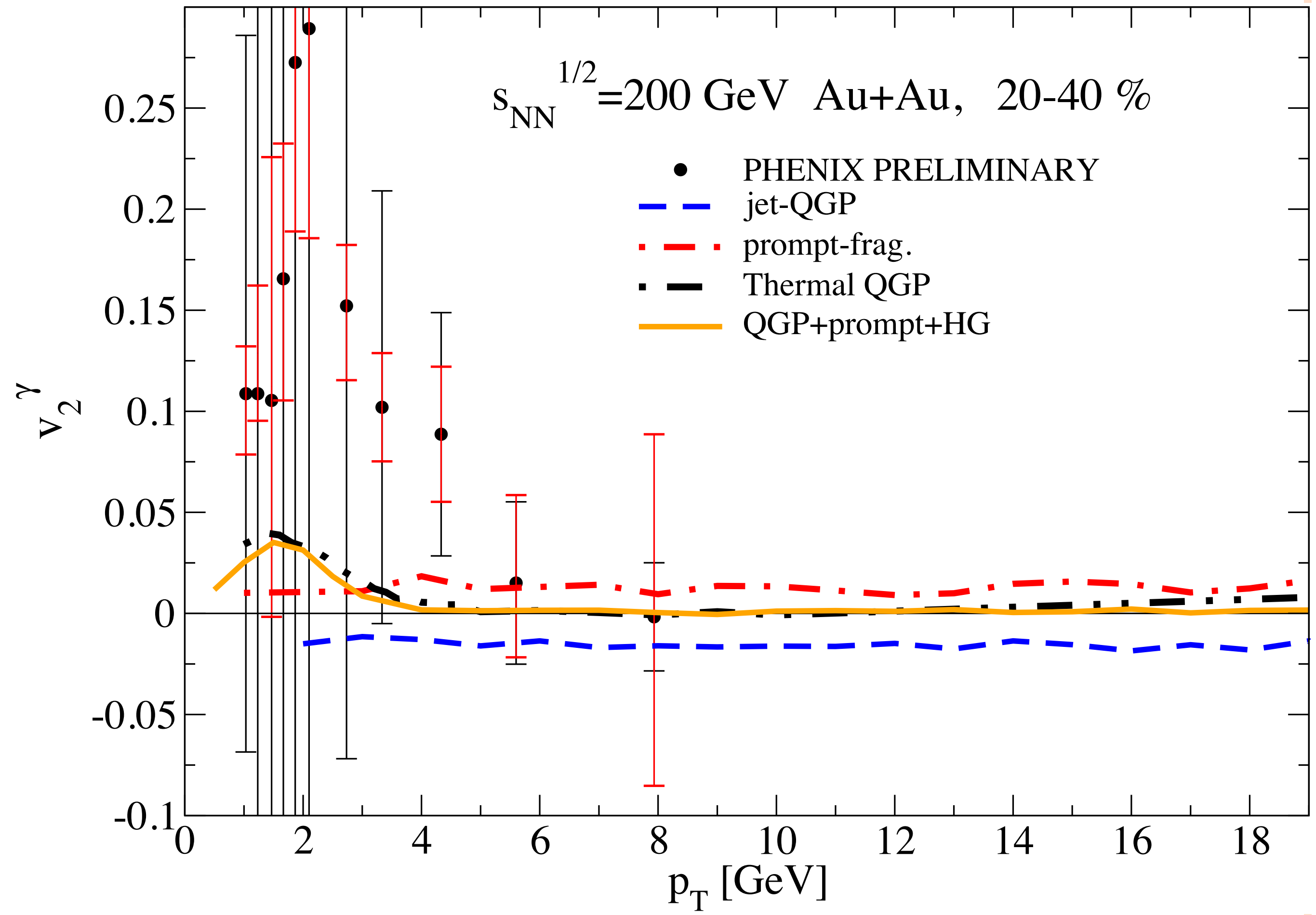
Knowing rates alone is not enough to guarantee predictive power or even characterization ability

Beyond simple spectra: Flow and correlations

$$\frac{dN}{p_T dp_T d\phi} = \frac{dN}{2\pi\, p_T dp_T}\left[1 + \sum_n 2 v_n \cos(n\phi)\right]$$



- Soft photons will go with the flow
- Jet-plasma photons: a negative v_2
- Details will matter: flow, T(t). . .



Turbide, Gale, Fries PRL (2006)
Low p_T: Chatterjee *et al.*, PRL (2006)
All p_T: Turbide *et al.*, PRC (2008)

Progress in Characterization tool: 3D Viscous Relativistic Hydrodynamics

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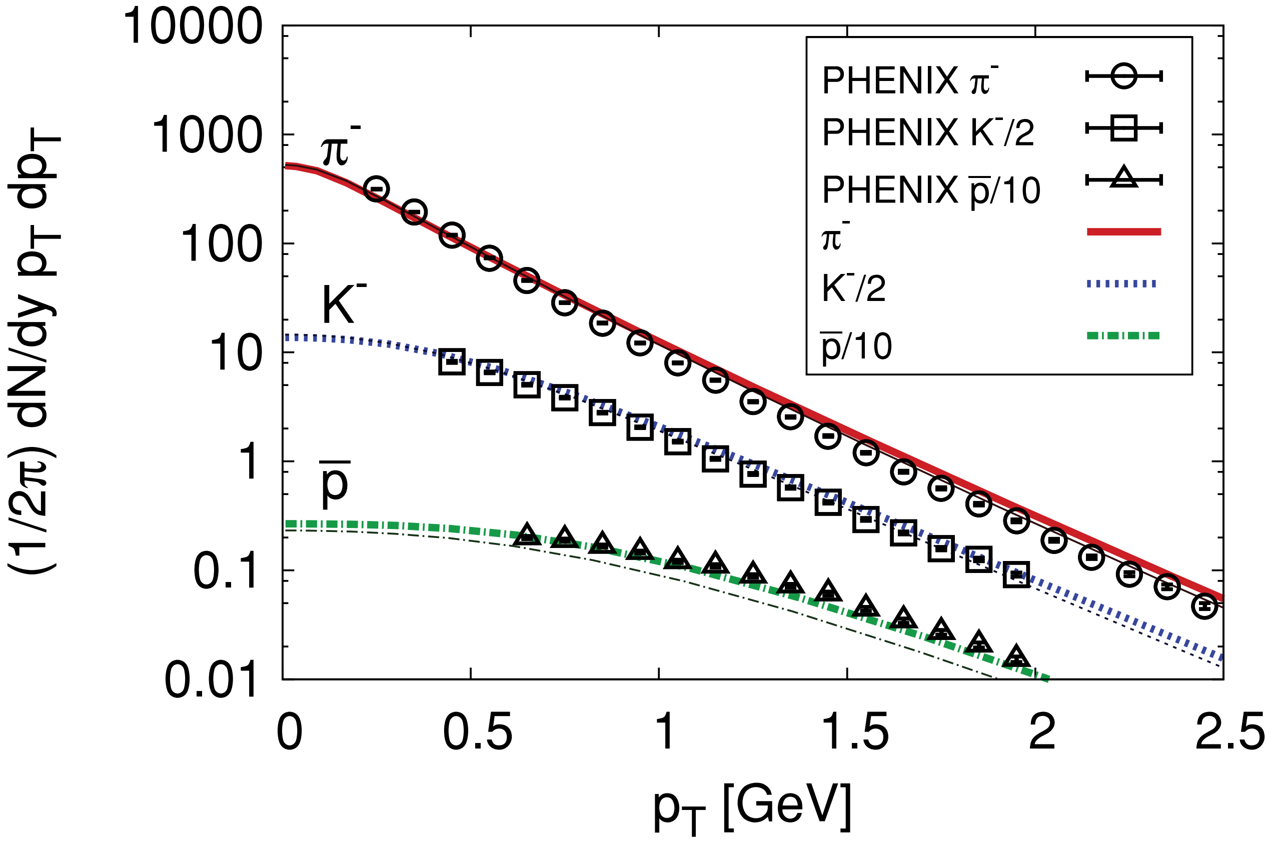

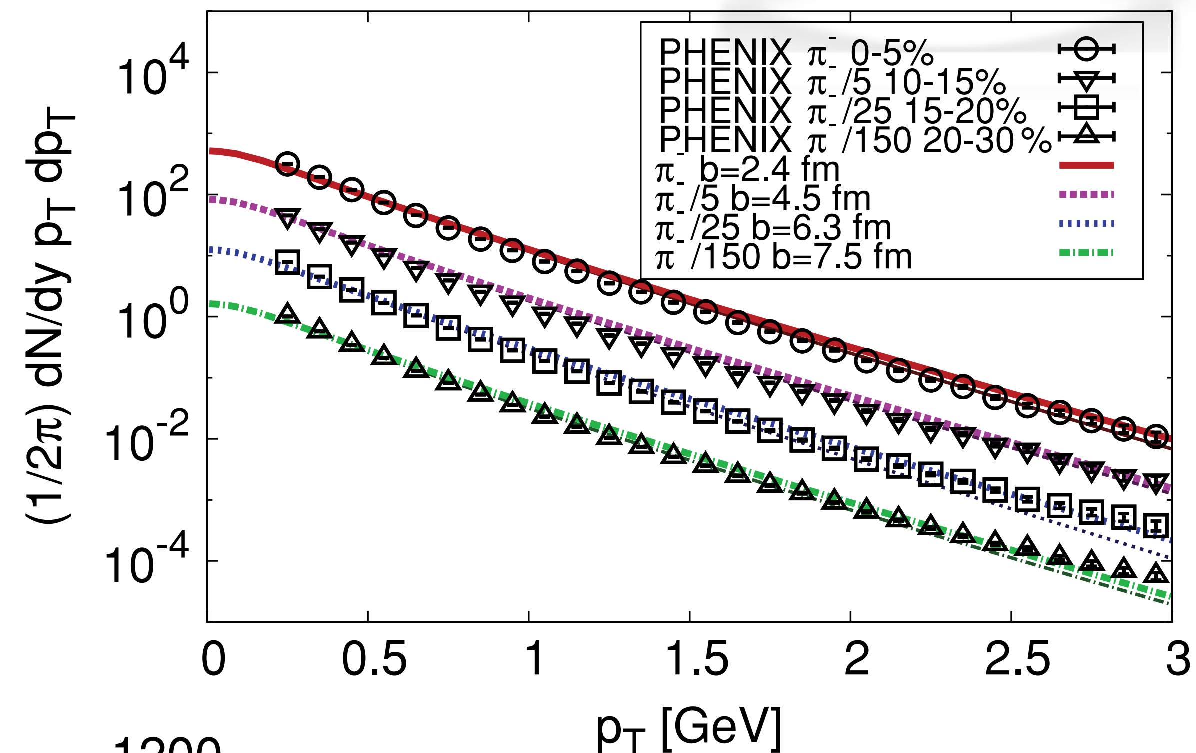

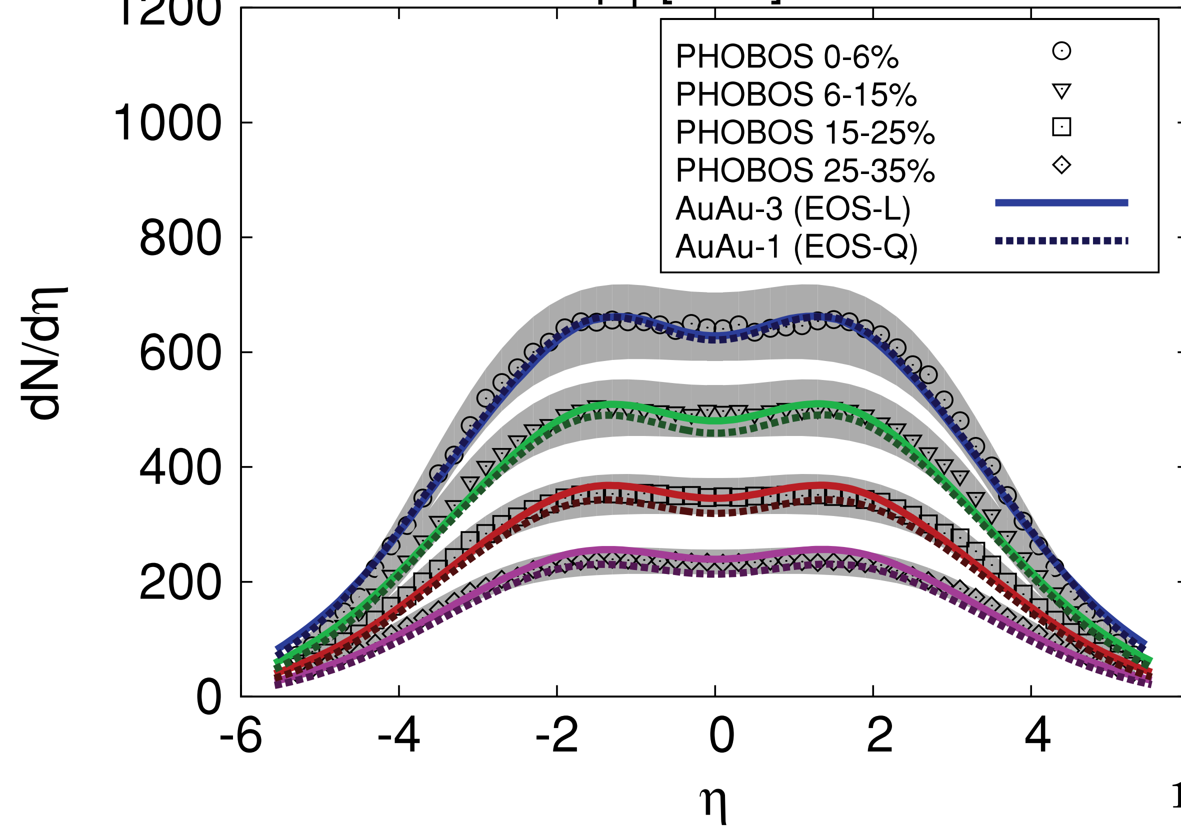

- MUSIC: 3D relativistic hydro
  - Ideal: Schenke, Jeon, and Gale, PRC (2010)
  - FIC and Viscous: Schenke, Jeon, Gale, PRL (2011)

Viscosity effects on EM observables?

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PROGRESS

Progress in Characterization tool: 3D Viscous Relativistic Hydrodynamics

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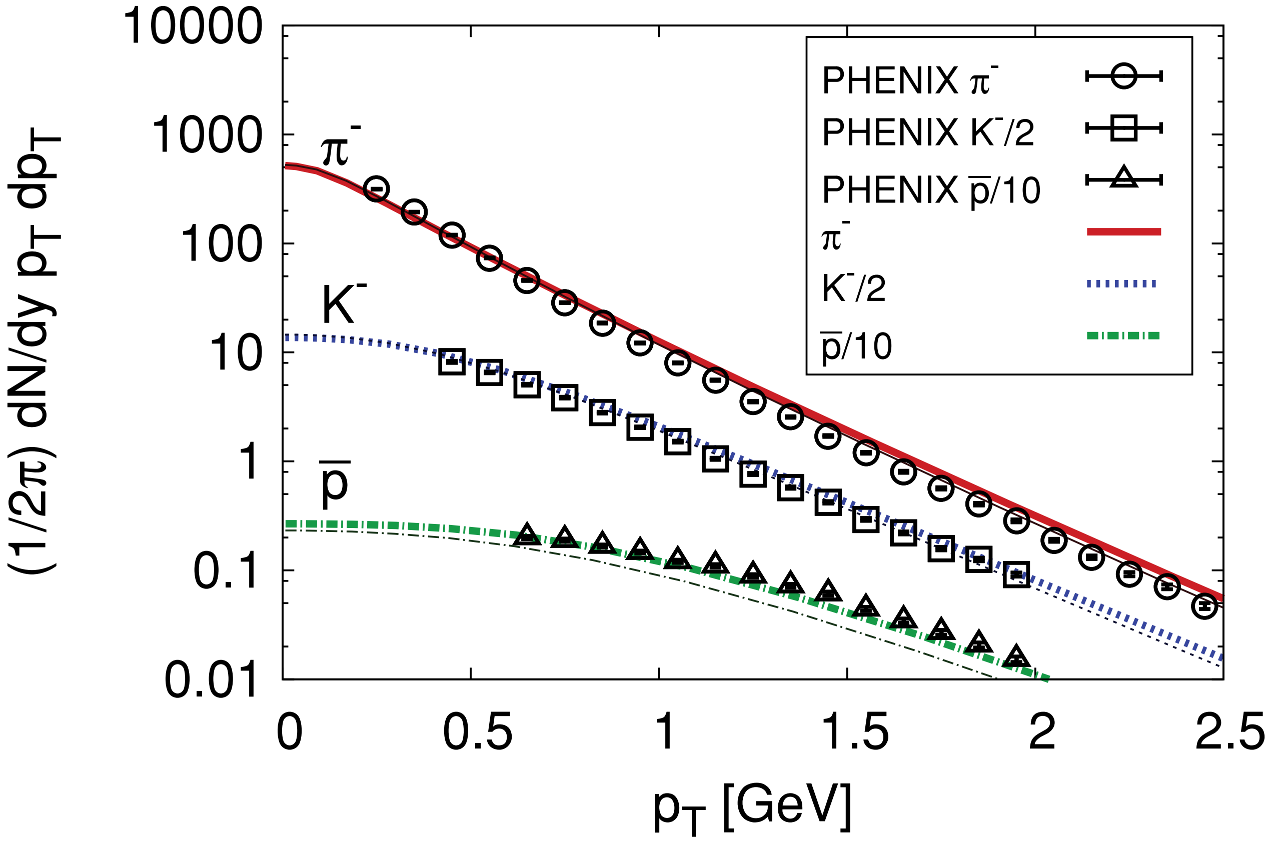

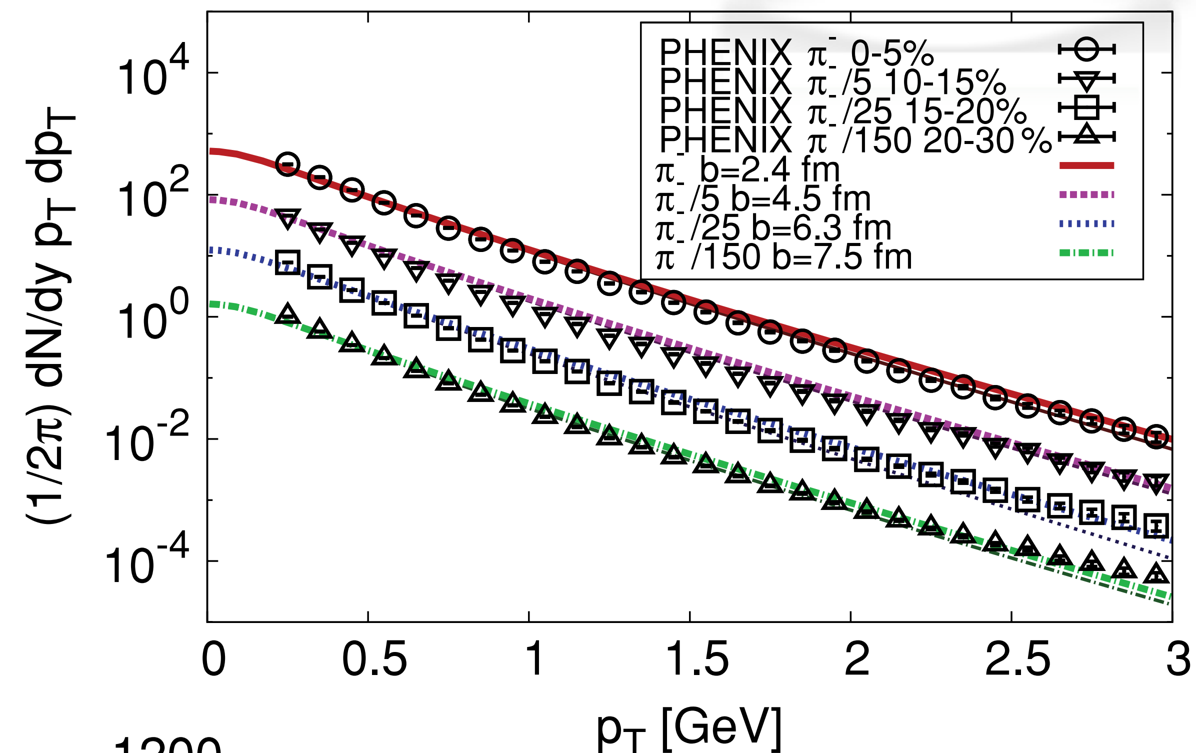

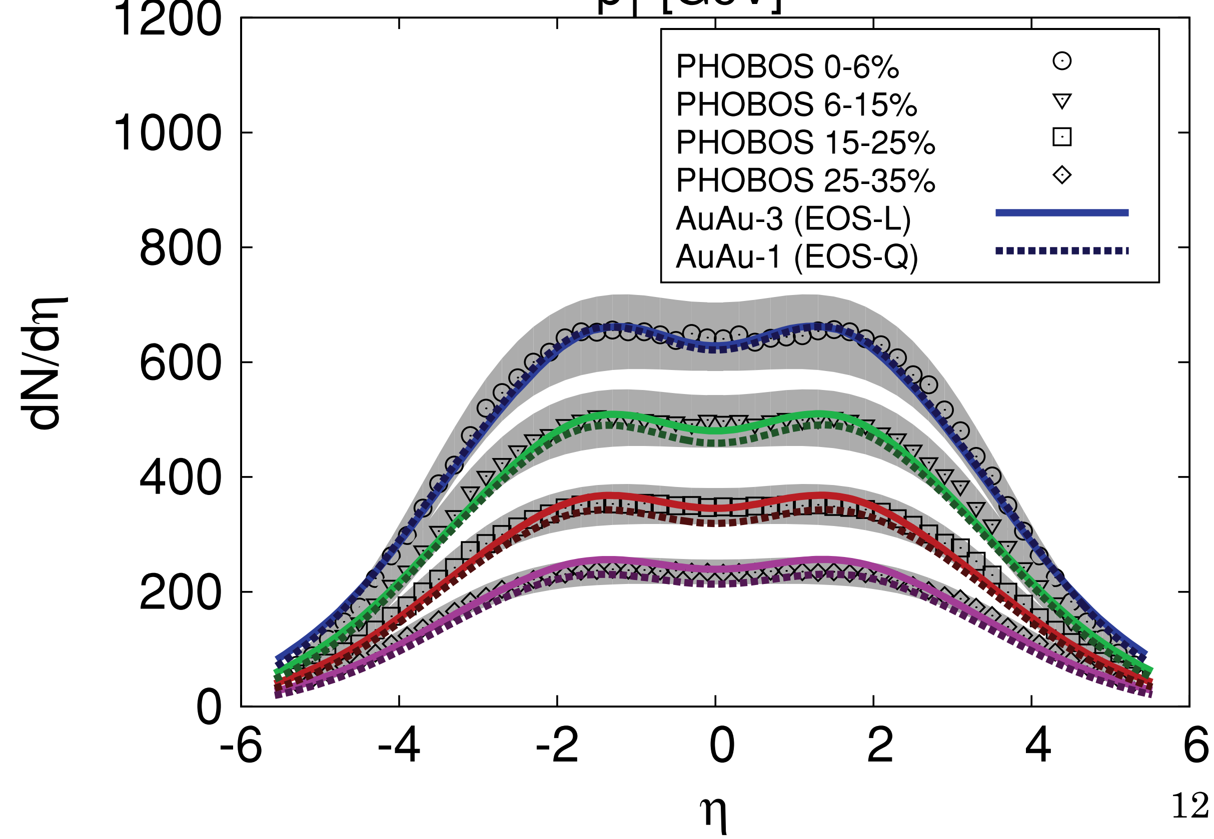

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Viscosity effects on EM observables?

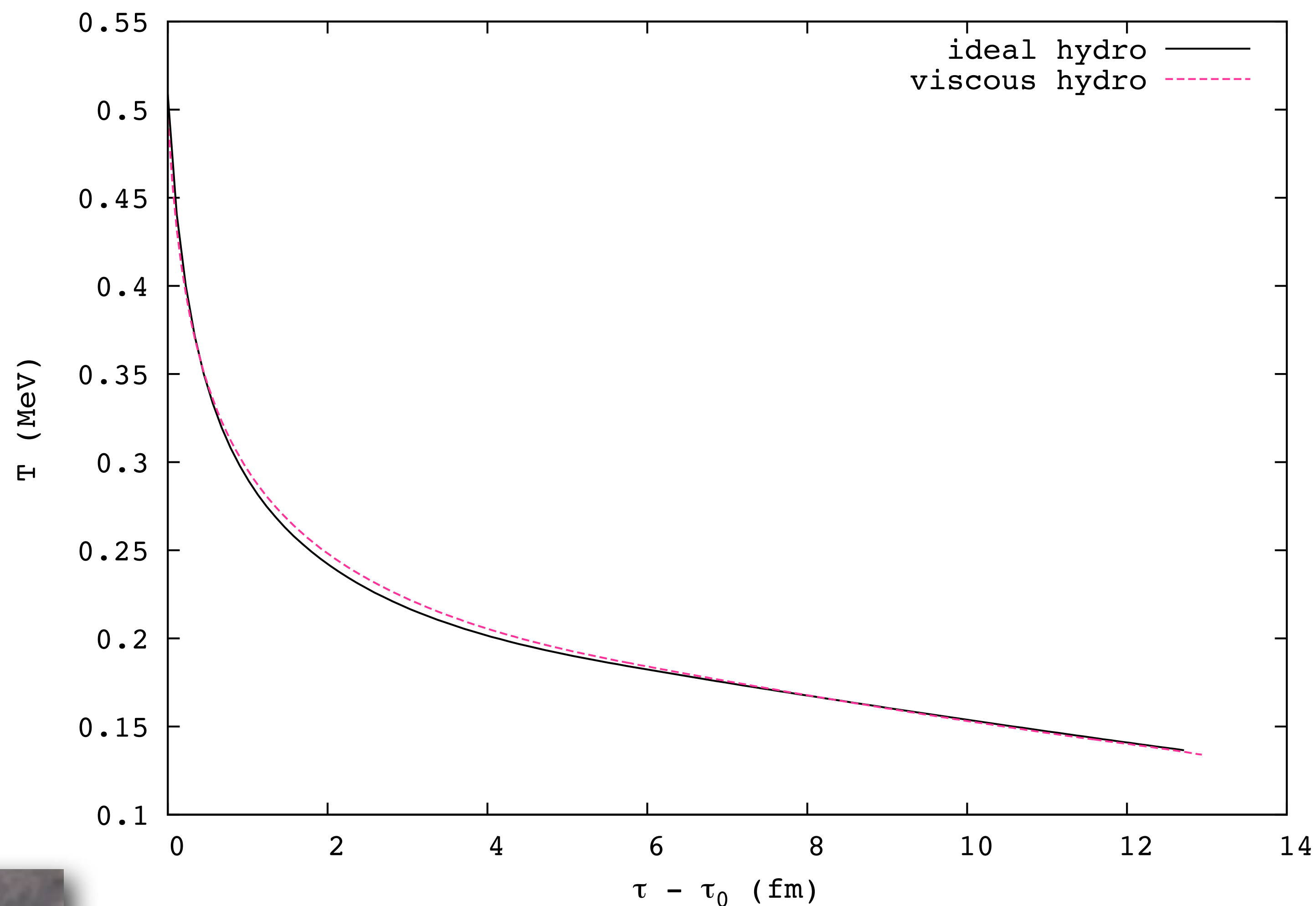
THE EFFECTS OF SHEAR VISCOSITY ON BULK DYNAMICS

$$T^{\mu\nu}_{\text{ideal}} = (\varepsilon + P)u^{\mu}u^{\nu} - Pg^{\mu\nu}$$

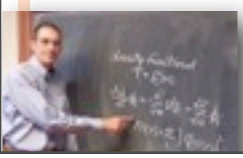
$$T^{\mu\nu} = T^{\mu\nu}_{\text{ideal}} + \pi^{\mu\nu}$$

Israël & Stewart, Ann. Phys. (1979), Baier et al., JHEP (2008), Luzum and Romatschke, PRC (2008)

$$\partial_{\mu}(su^{\mu}) \propto \eta$$



- Viscous evolution starts with a lower T
- T drop is slower than ideal case



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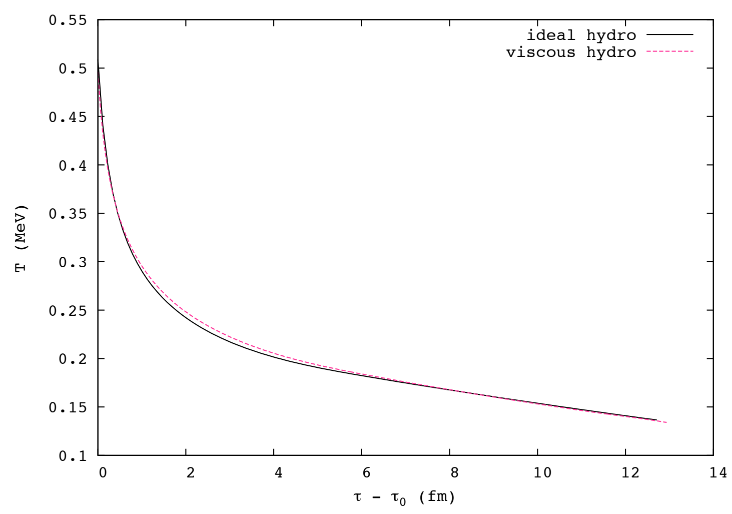

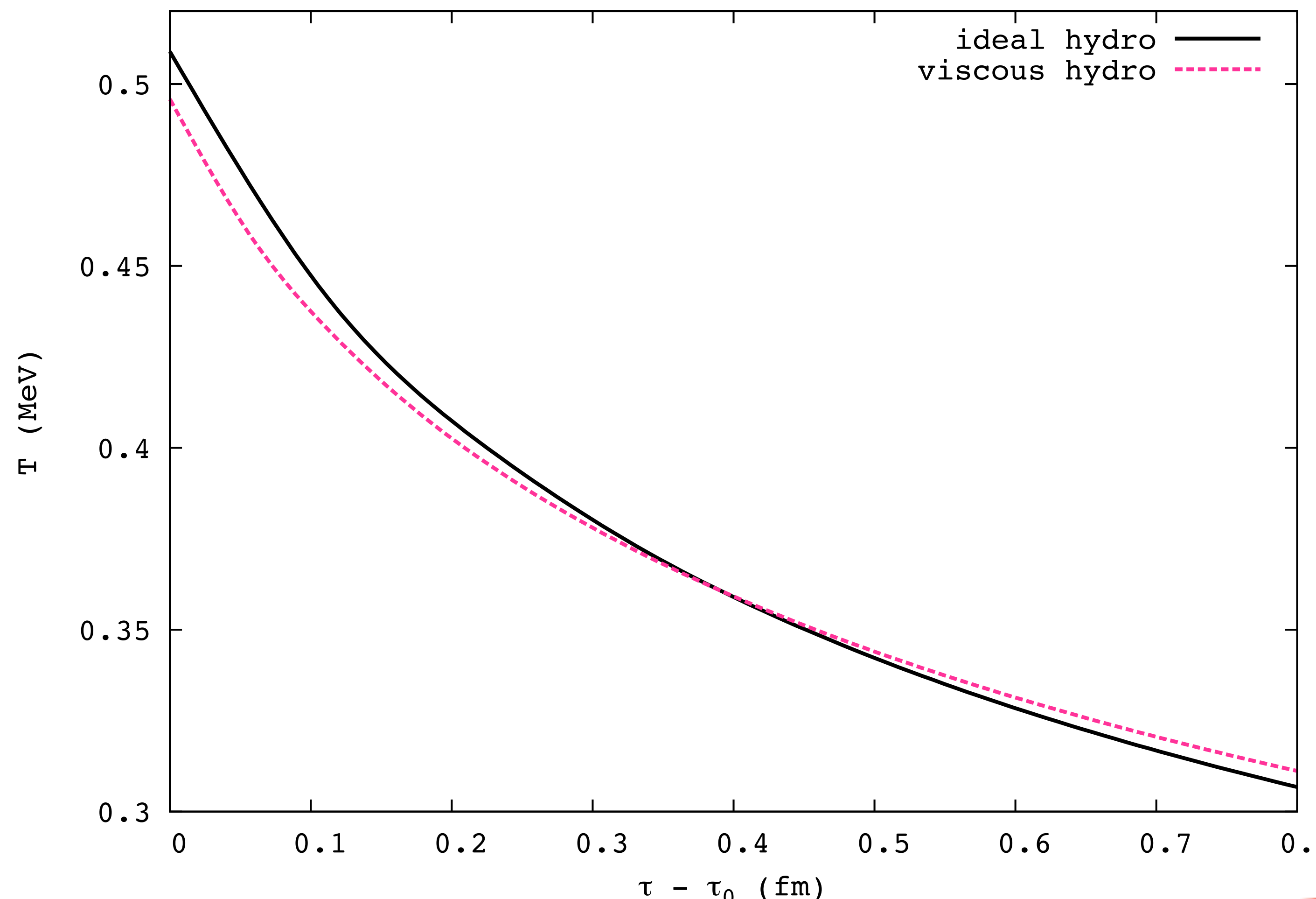

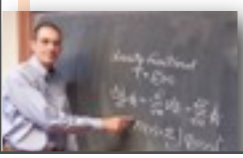

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THE EFFECTS OF SHEAR VISCOSITY ON THE PHOTON DISTRIBUTION

In-medium **hadrons**:

$$f_0(u^\mu p_\mu) = \frac{1}{(2\pi)^3}\frac{1}{\exp[(u^\mu p_\mu - \mu)/T] \pm 1}$$

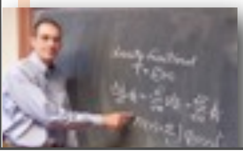
$$f \to f_0 + \delta f, \quad \delta f = f_0(1 \pm (2\pi)^3 f_0) p^\alpha p^\beta \pi_{\alpha\beta} \frac{1}{2(\varepsilon + P)T^2}$$

$$q_0 \frac{d^3R}{d^3q} = \int \frac{d^3p_1}{2(2\pi)^3 E_1} \frac{d^3p_2}{2(2\pi)^3 E_2} \frac{d^3p_3}{2(2\pi)^3 E_3} (2\pi)^4 |M|^2 \delta^4(\ldots) \frac{f(E_1)f(E_2)[1 \pm f(E_3)]}{2(2\pi)^3}$$

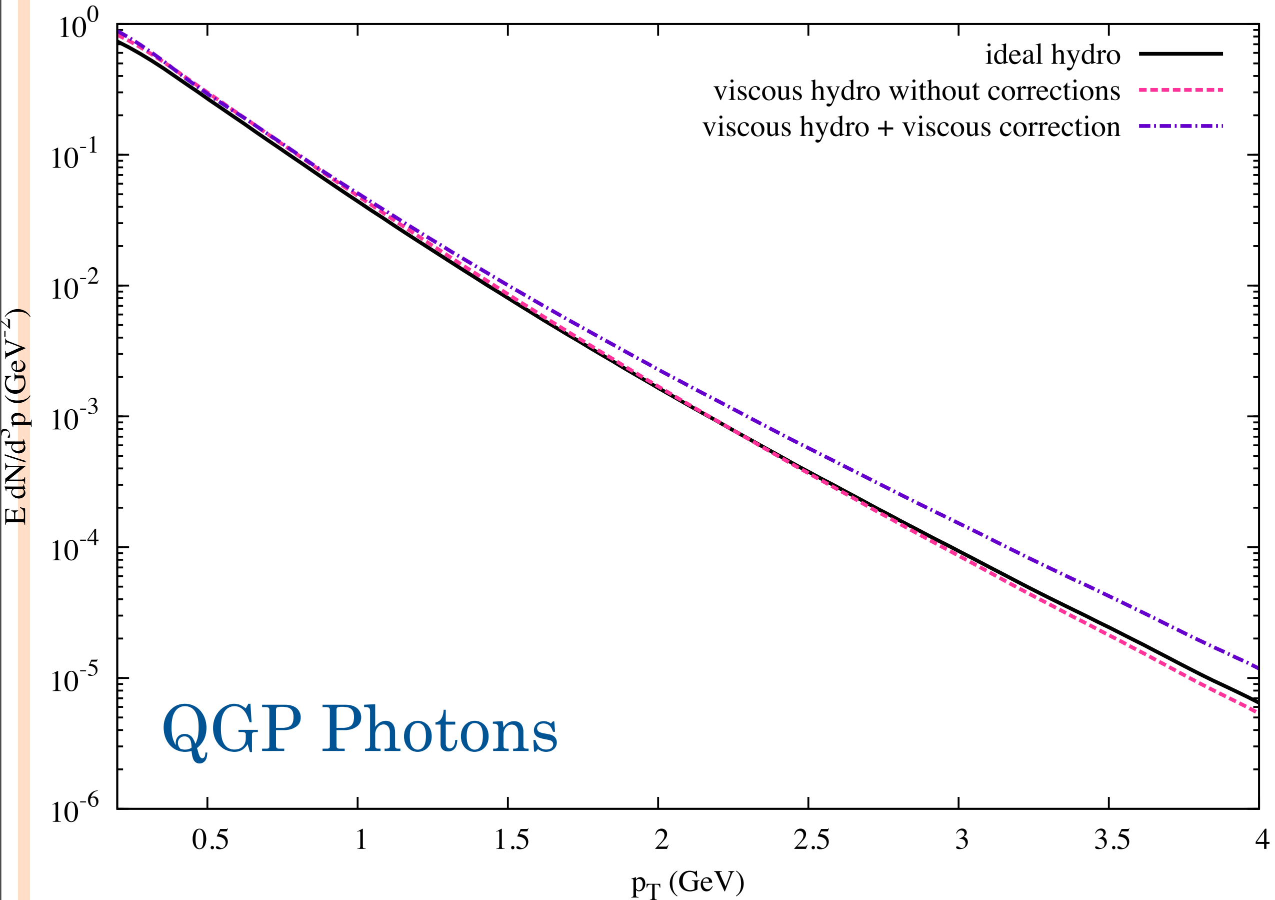
One considers all the reaction and radiative decay channels of external state combinations of:

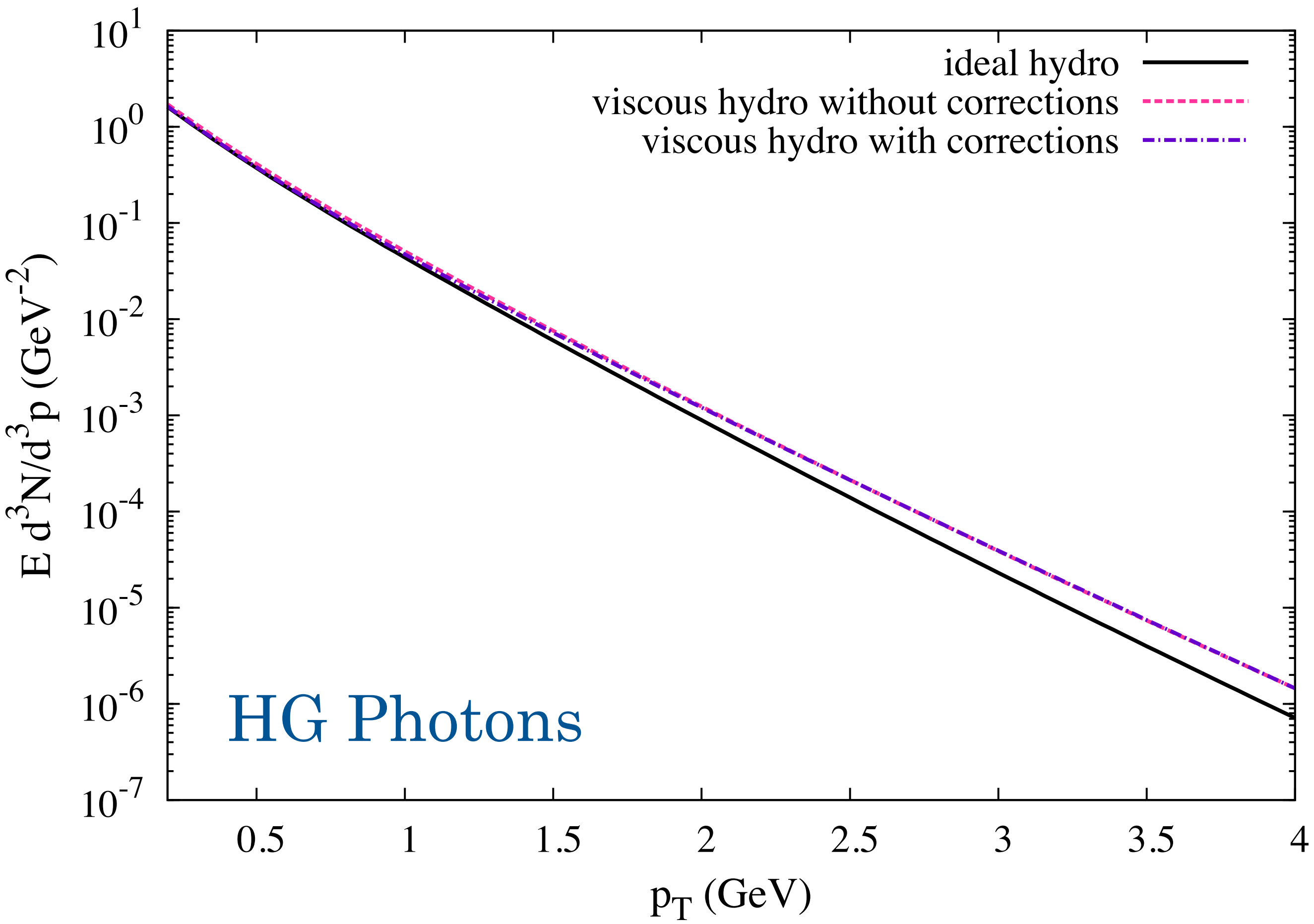
$\{\pi, K, \rho, K^*, a_1\}$ With hadronic form factors

+ QGP Photons



The effects of shear viscosity on the photon distribution

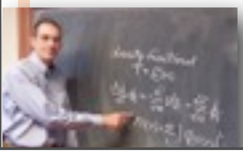




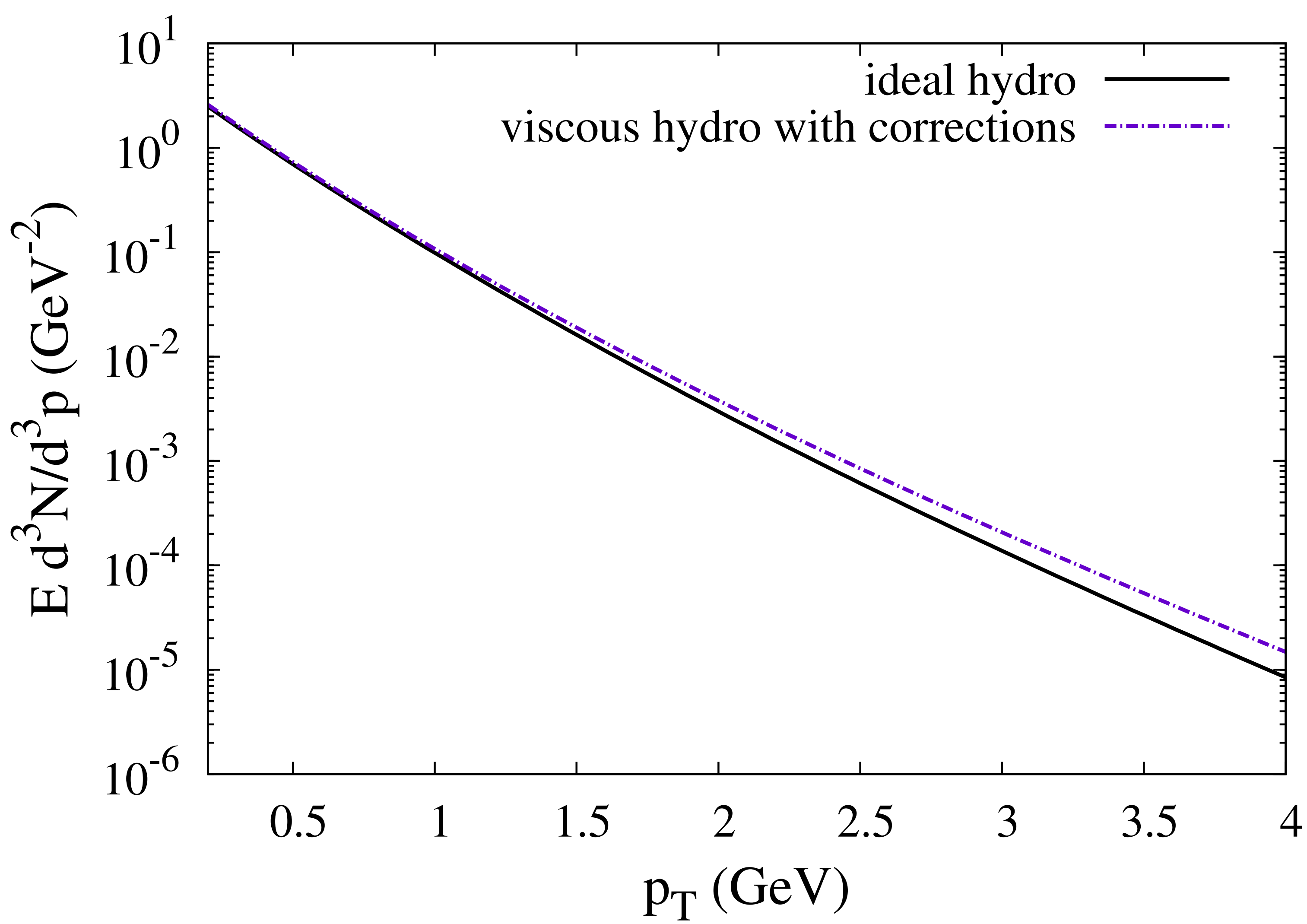
K. Dusling NPA (2010)
Chaudhuri & Sinha, PRC (2011)

Viscous effects harden the photon spectrum

M. Dion et al., PRC (2011)

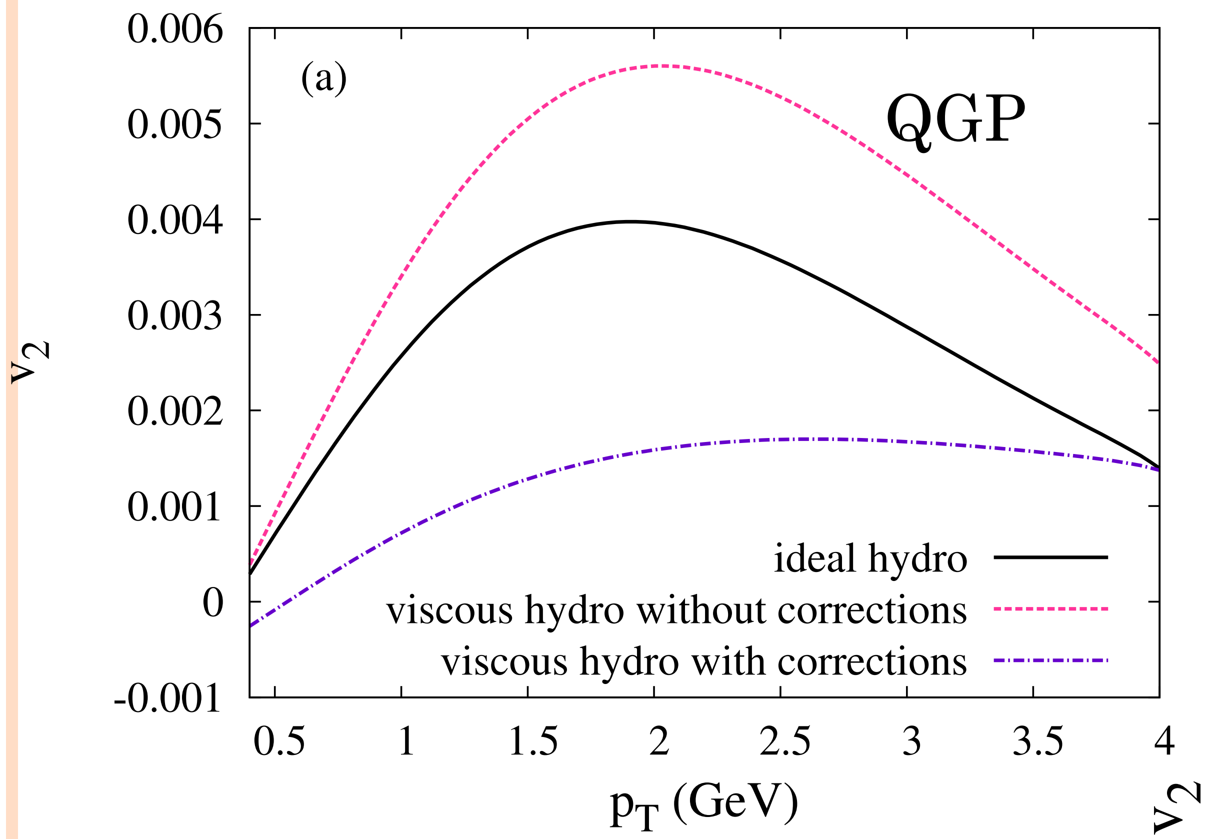


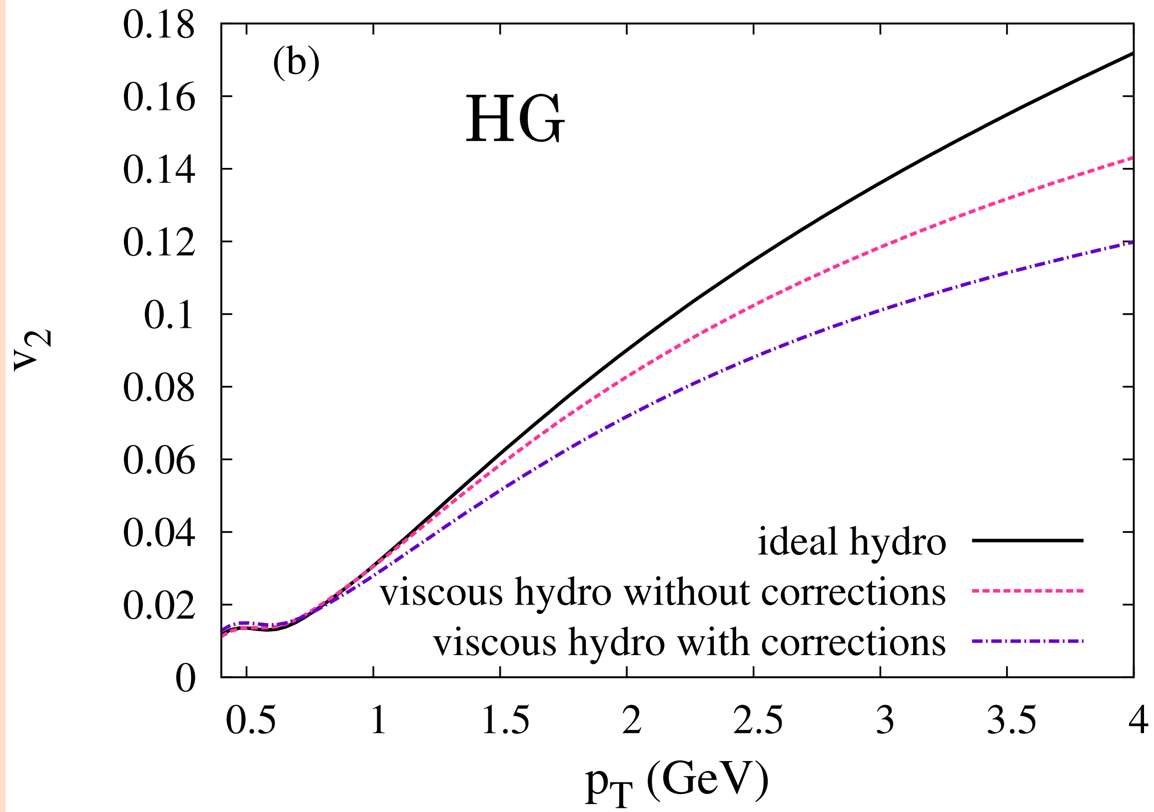
THE NET THERMAL PHOTON YIELD

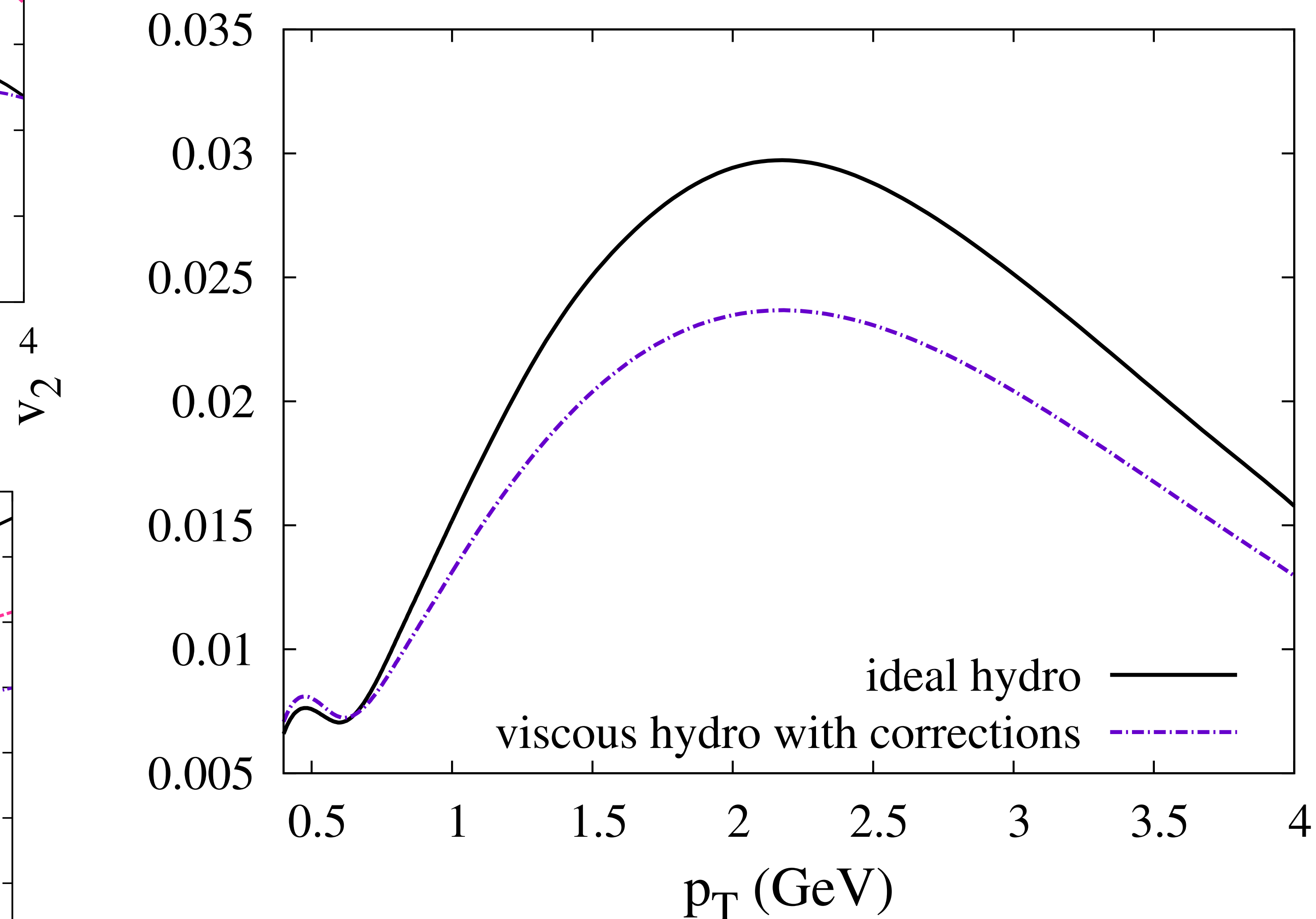


- Viscous corrections make the spectrum harder, ≈100% at p_T = 4 GeV.
- Increase in the slope of ≈15% at p_T = 2 GeV.
- Extracting the viscosity from the photon spectra will be challenging
- Once pQCD photons are included: a few % effect from viscosity
- More work is still needed to properly include all photon sources in a consistent way

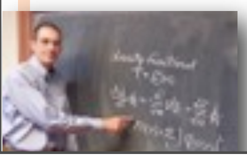
SHEAR VISCOSITY AND PHOTON V2



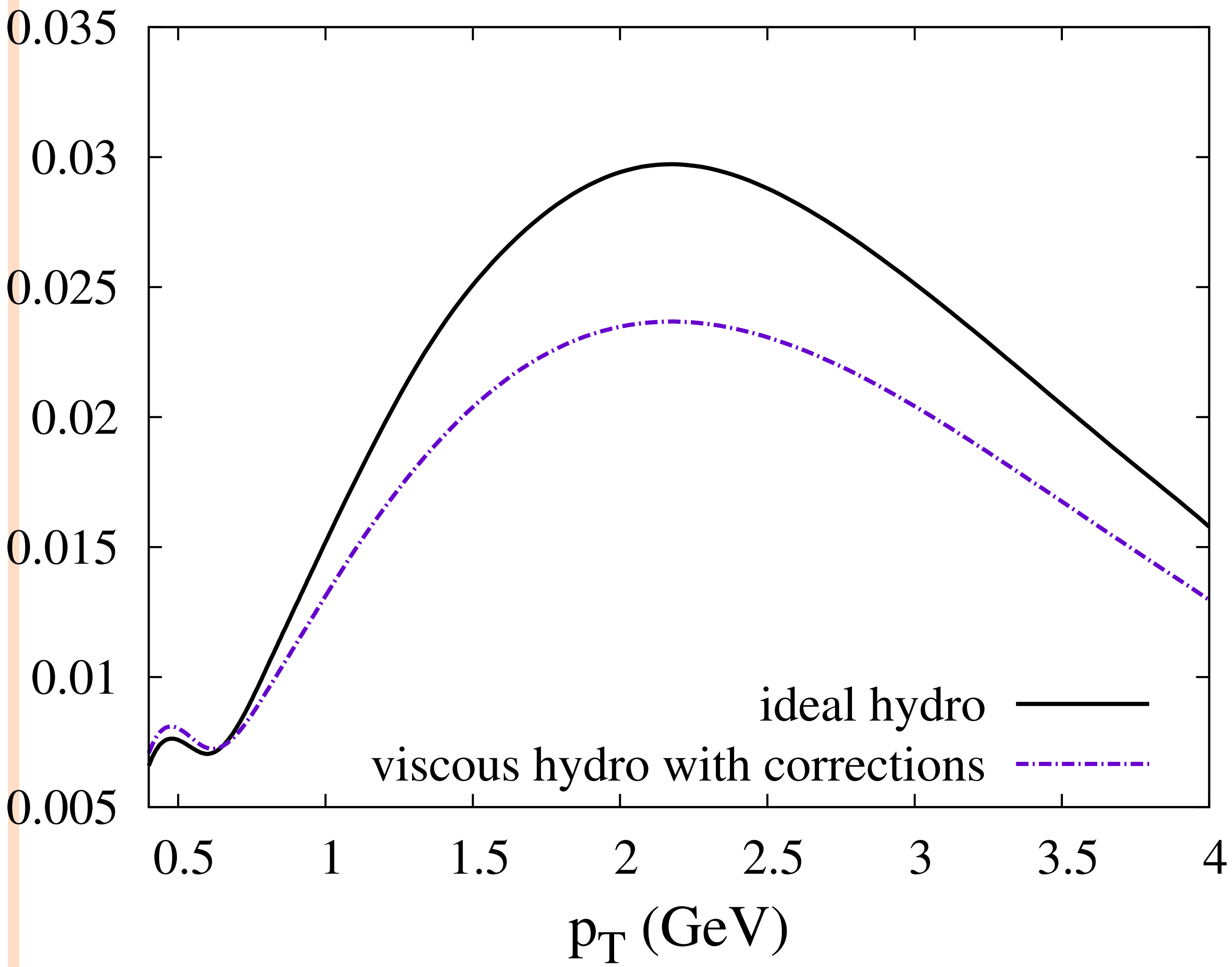




M. Dion *et al.*, PRC 2011

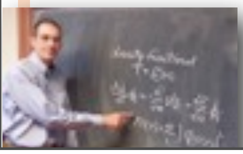


SHEAR VISCOSITY AND PHOTON V_2

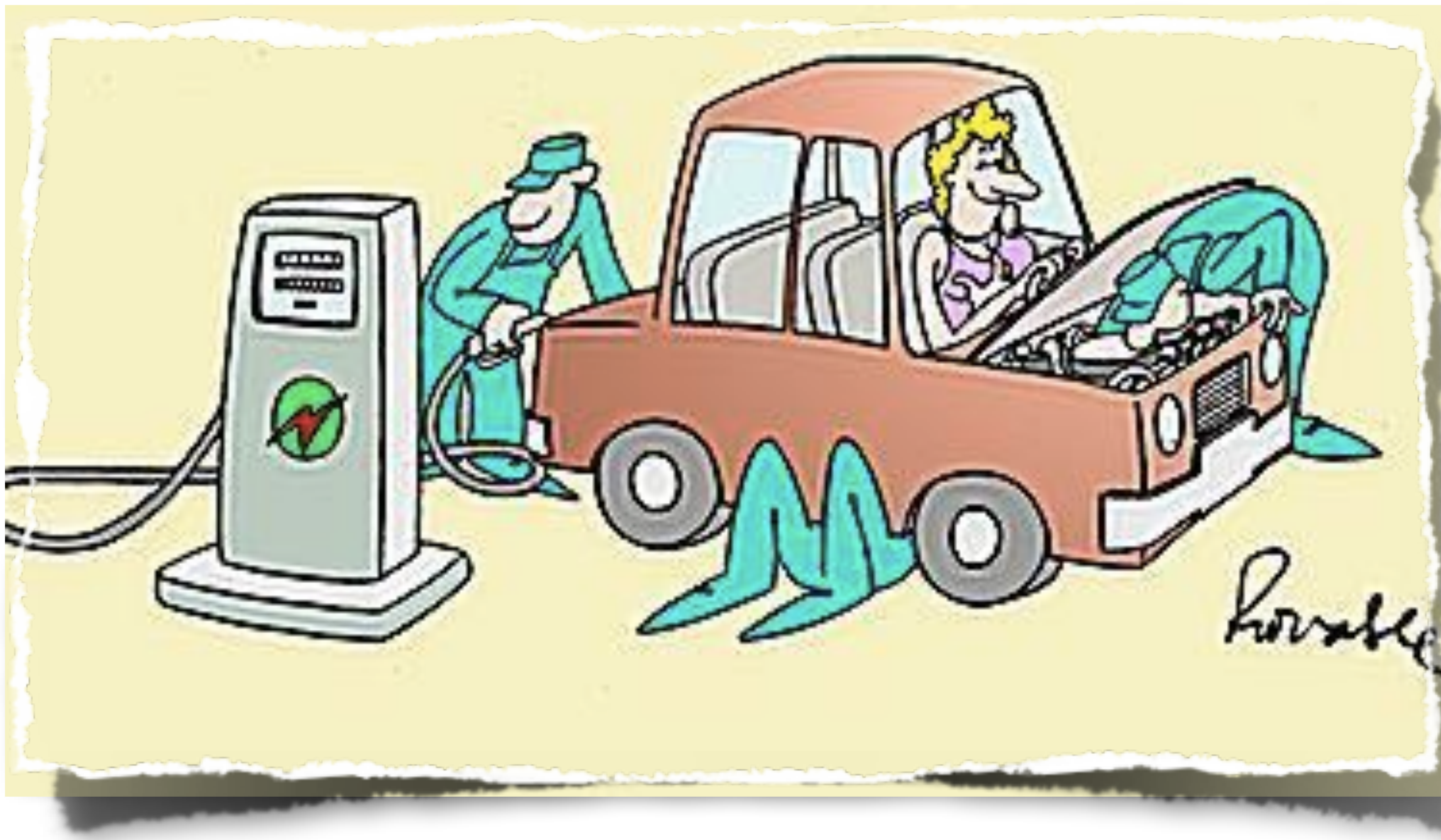


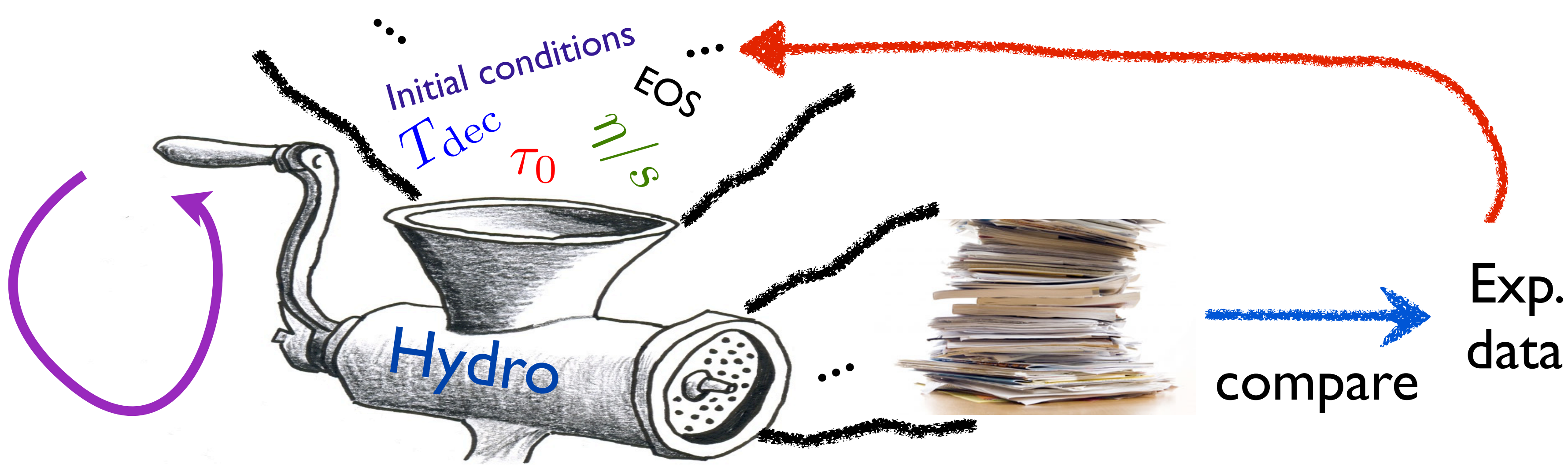
- The net elliptic flow is a *weighted average*. A larger QGP yield will yield a smaller v_2. Same story - *mutatis mutandis* - for the HG
- The turnover at $p_T \approx 2$ GeV is QGP-driven (*)
- The net effect of viscous corrections makes the photon elliptic flow smaller, as it does for hadrons

M. Dion *et al.*, PRC 2011



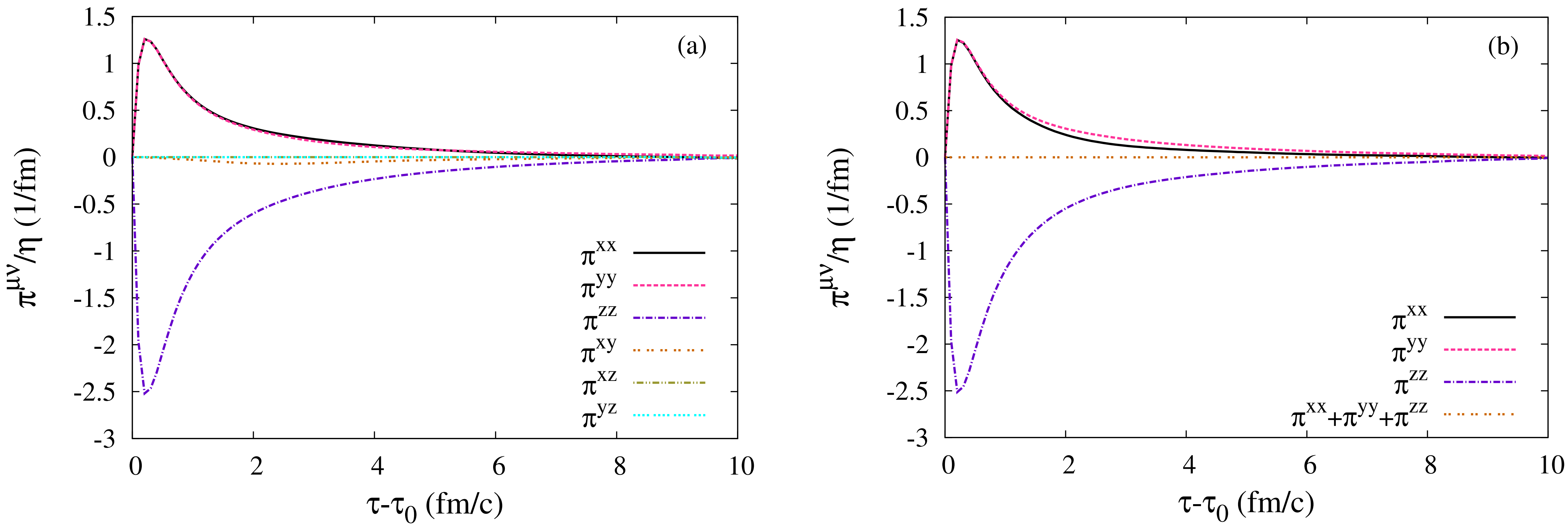
Looking under the hood: Non-equilibrium effects

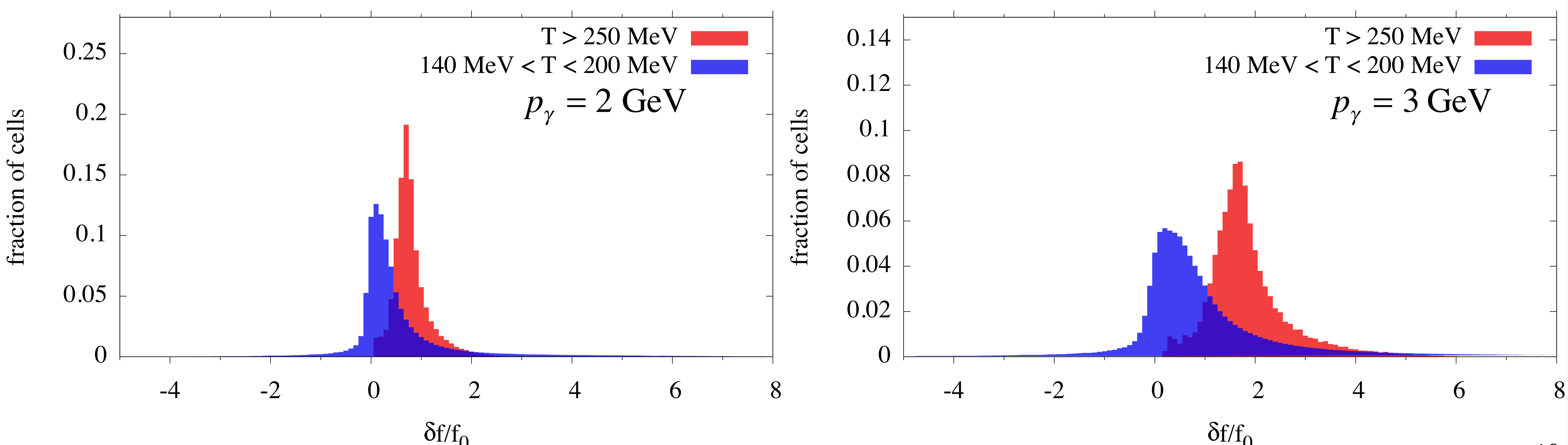




Chun Shen (OSU)

Looking under the hood: Non-equilibrium effects

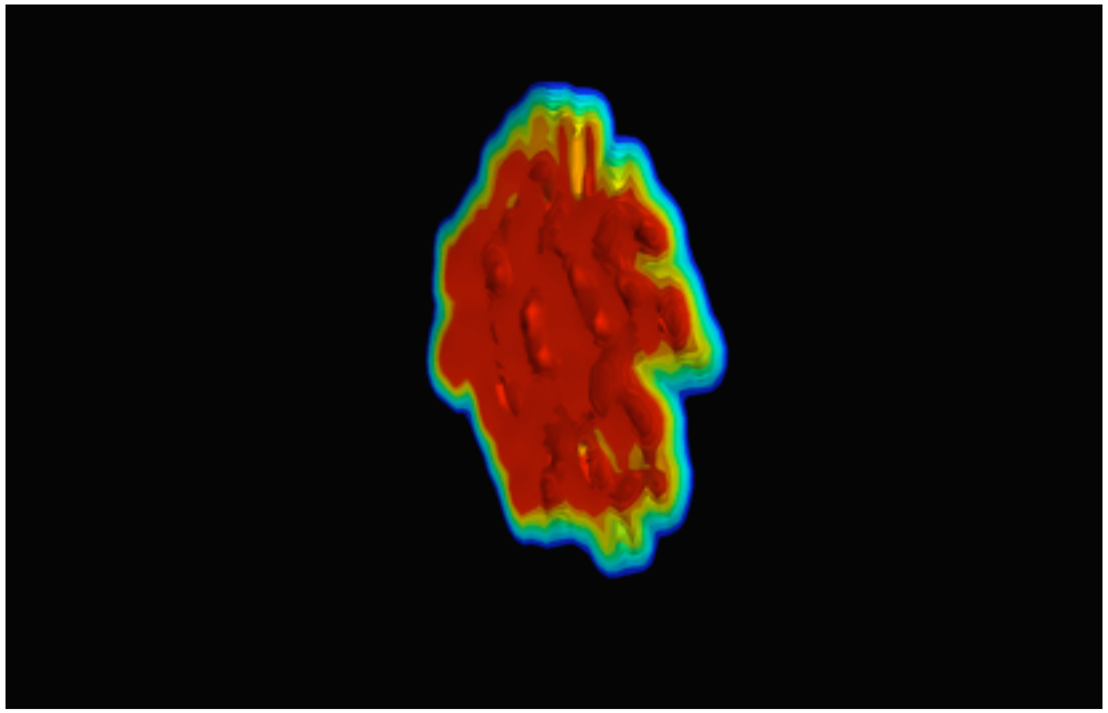


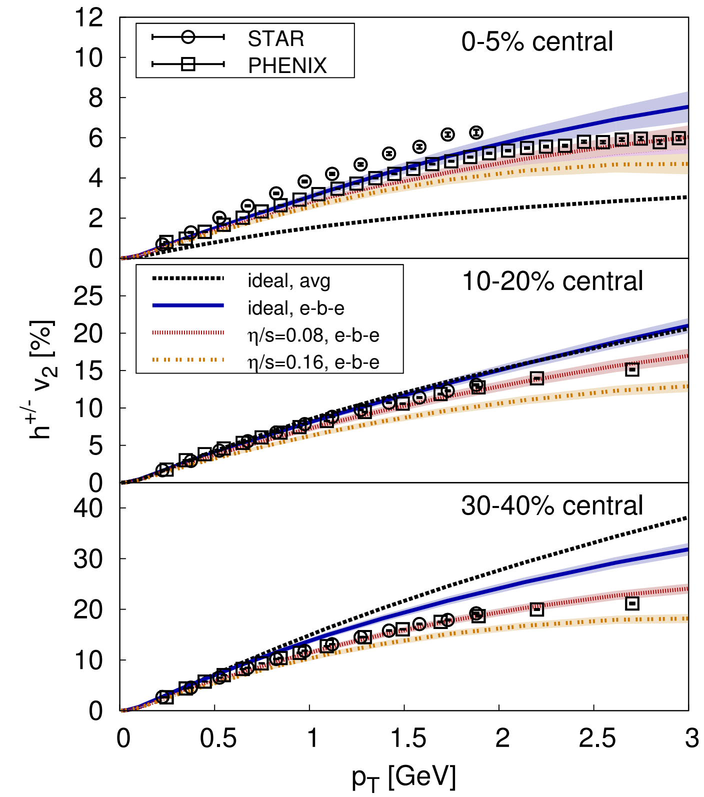


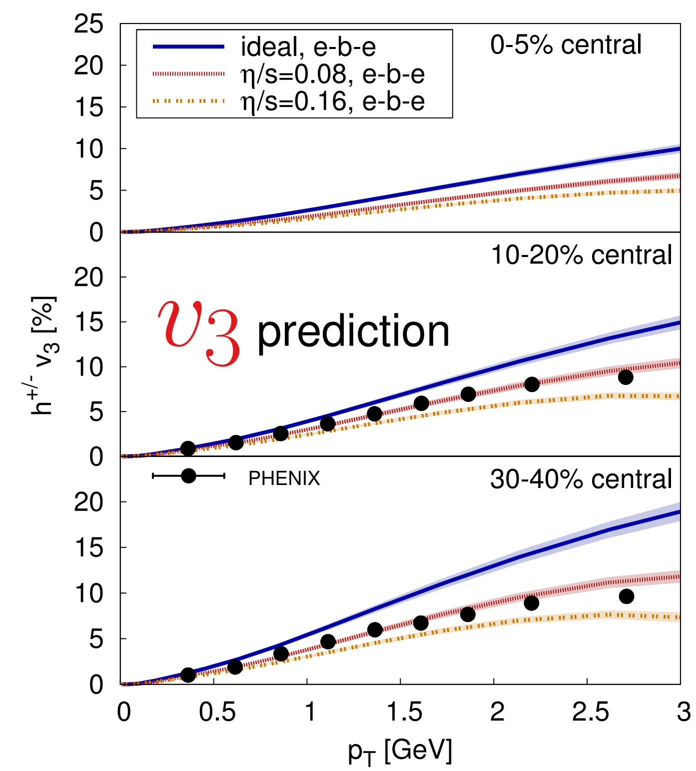
Charles Gale

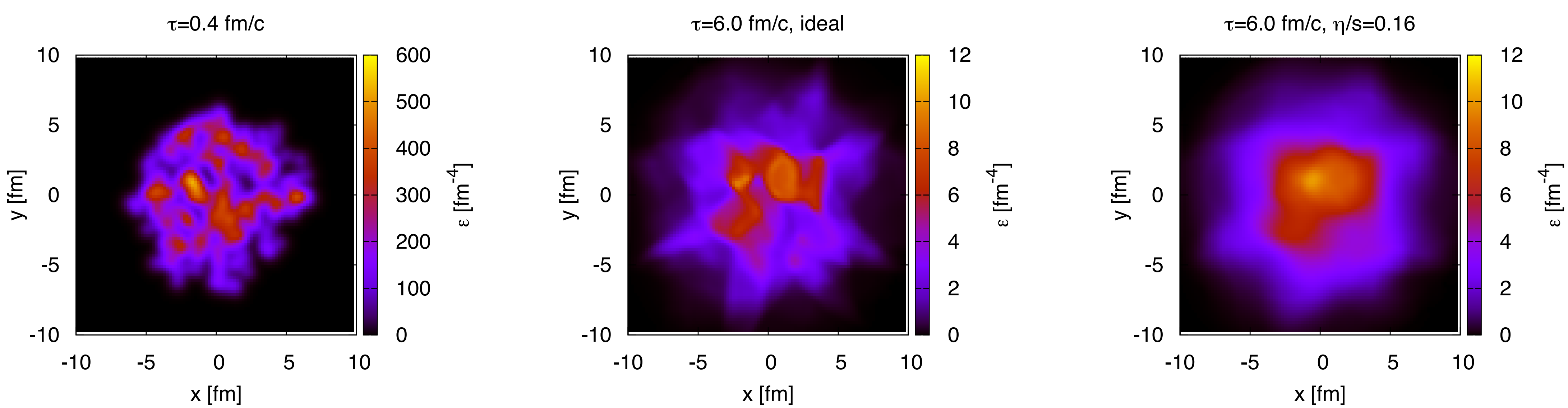
Initial state fluctuations: a paradigm shift in heavy ion analyses

Lumpy
MUSIC









Schenke, Jeon, Gale, PRL (2011)

Charles Gale

Initial state fluctuations: a paradigm shift in heavy ion analyses

Lumpy
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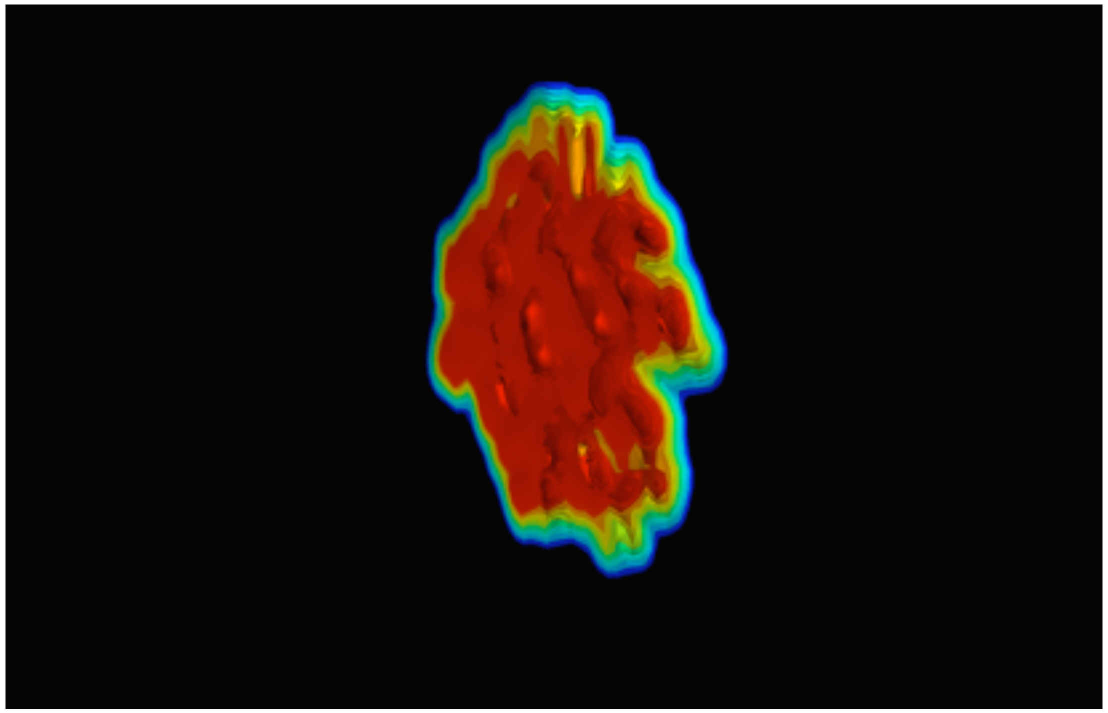
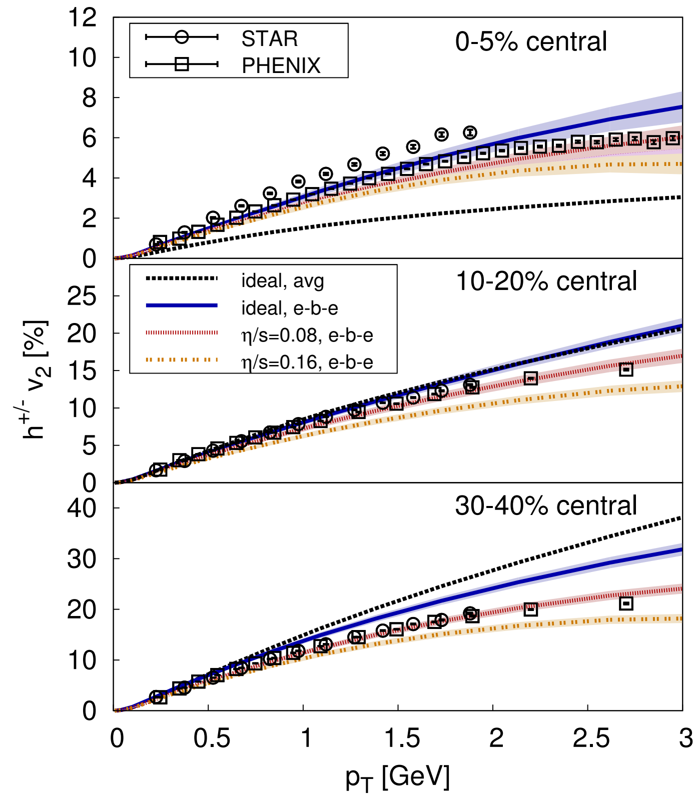
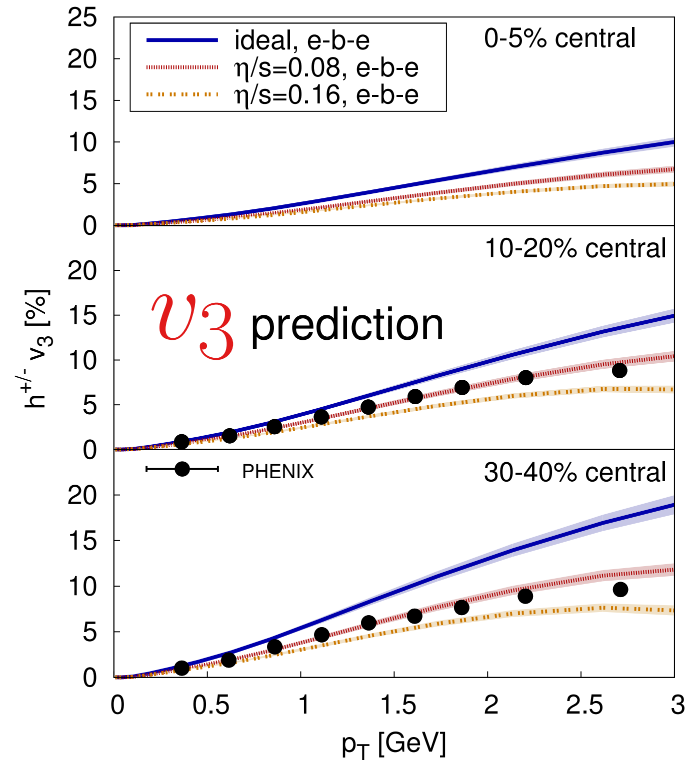
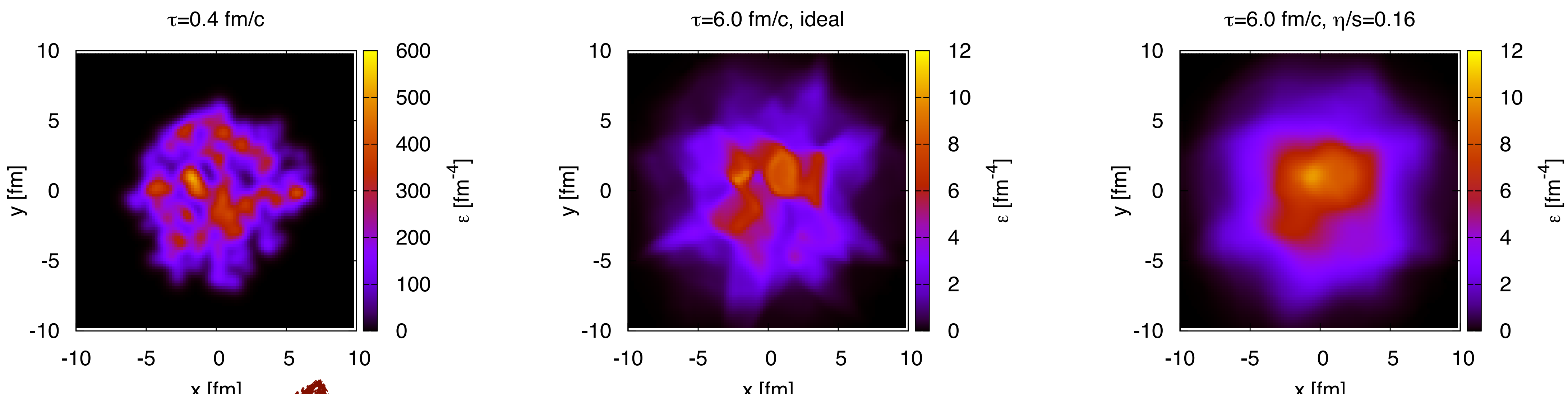






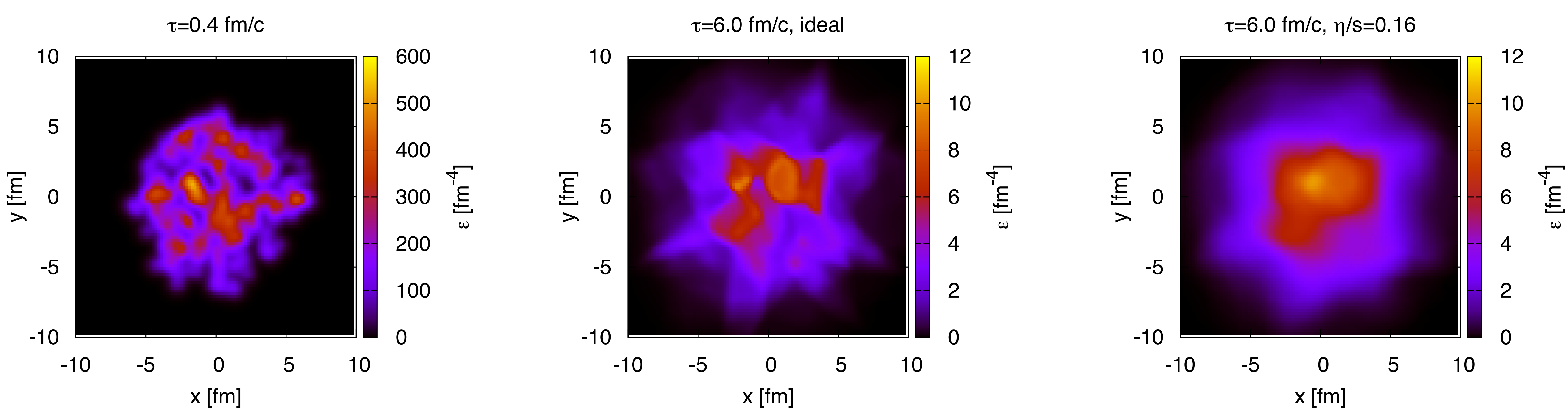


PROGRESS

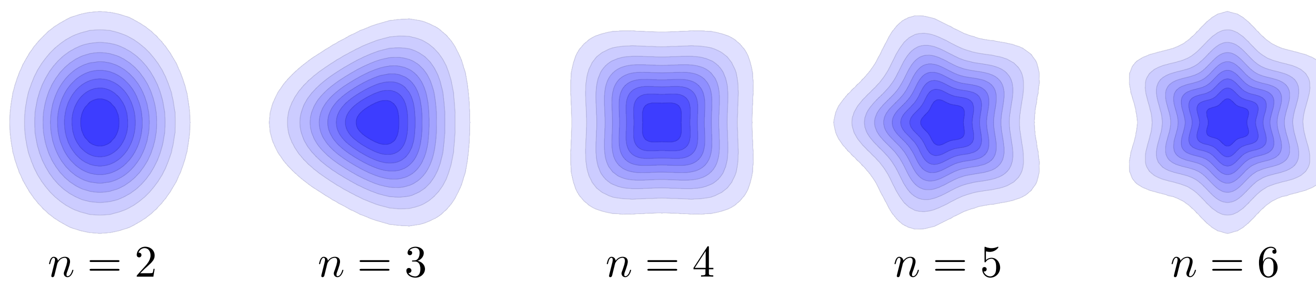
Schenke, Jeon, Gale, PRL (2011)

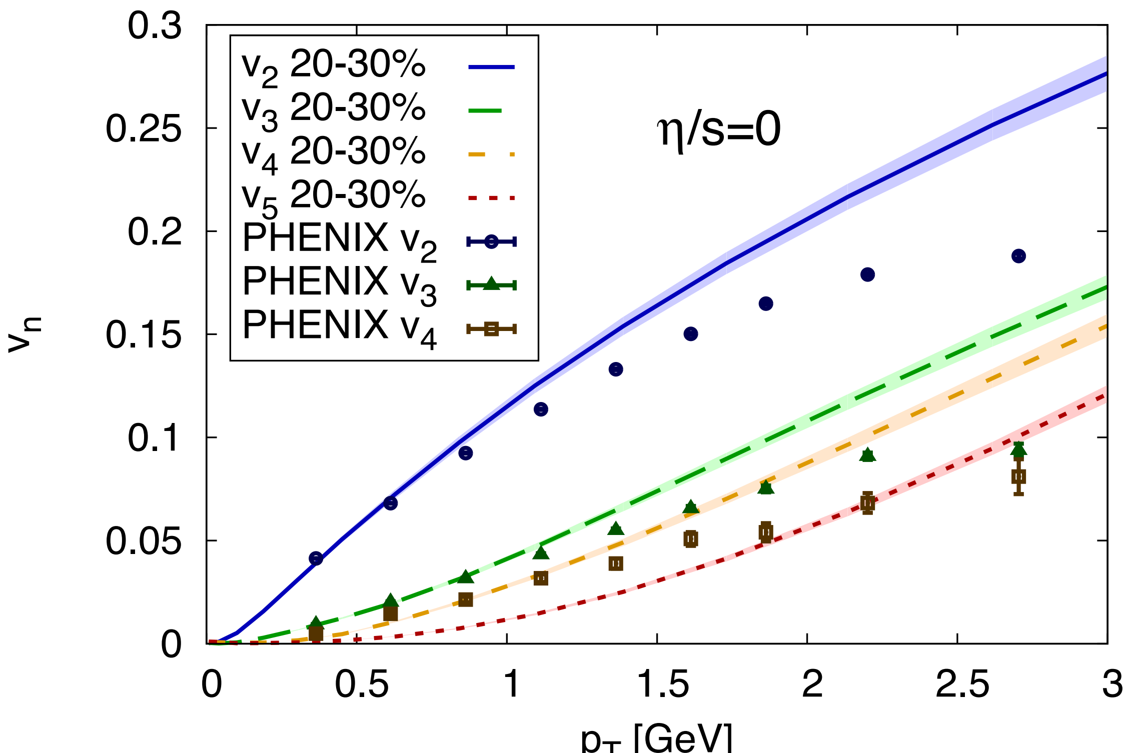
Initial state fluctuations: MC Glauber initialization

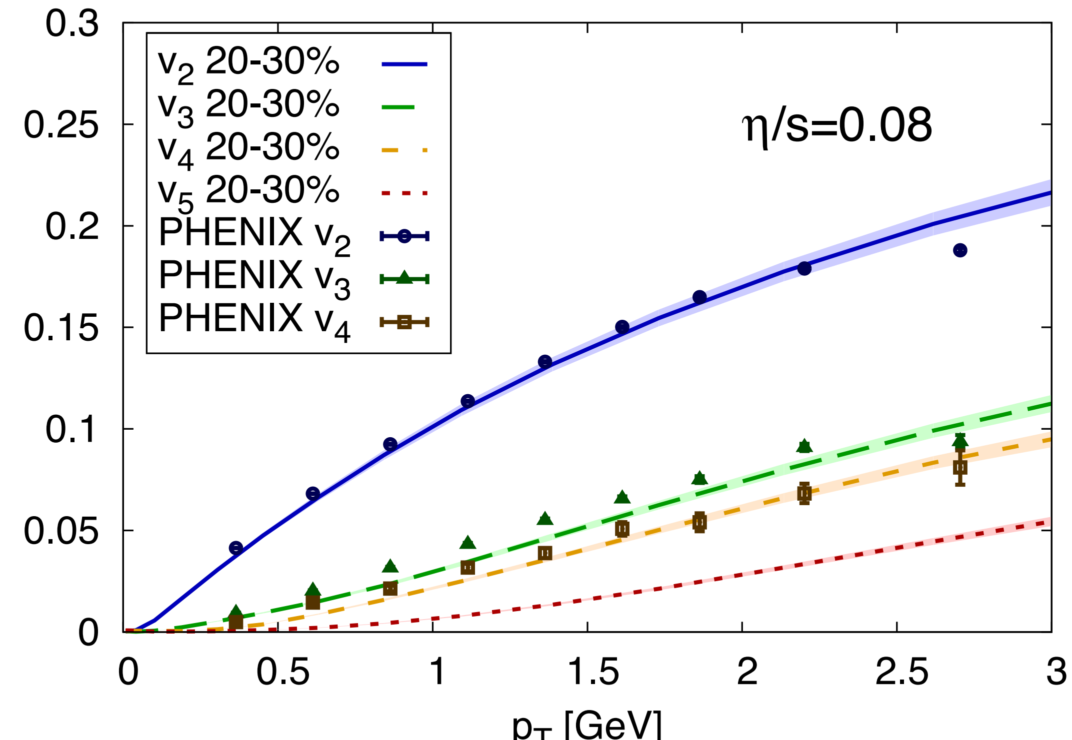
- Sample the nucleon locations from the nuclear density profile (with or without the shell effect deformations)
- Identify the colliding partners ($d \leq \sqrt{\sigma_{NN} / \pi}$)
- Having identified the wounded nucleons, ascribe an energy distribution at each site, with a Gaussian width σ_0 .

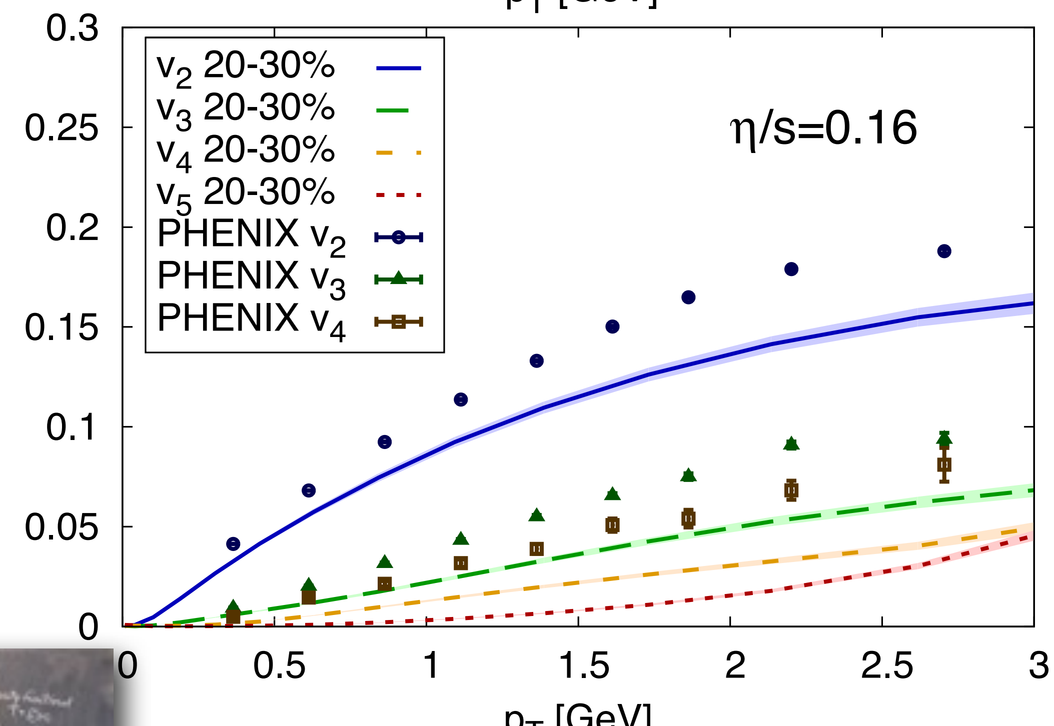


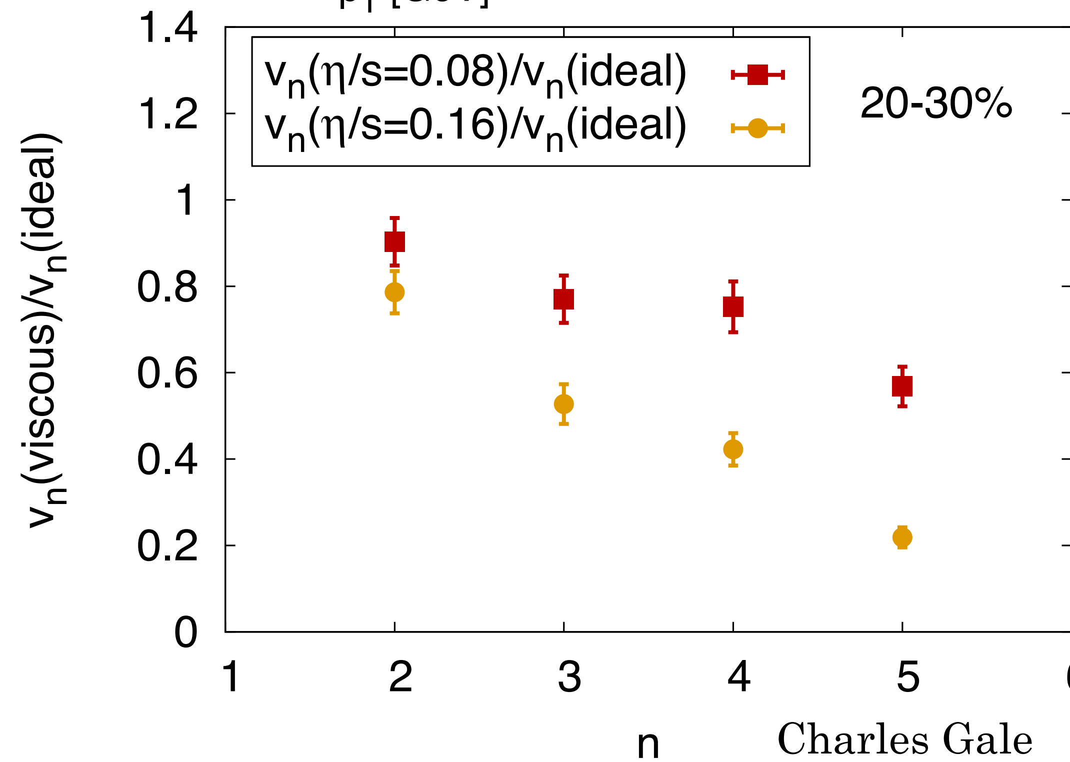
Moving into the "characterization" phase...





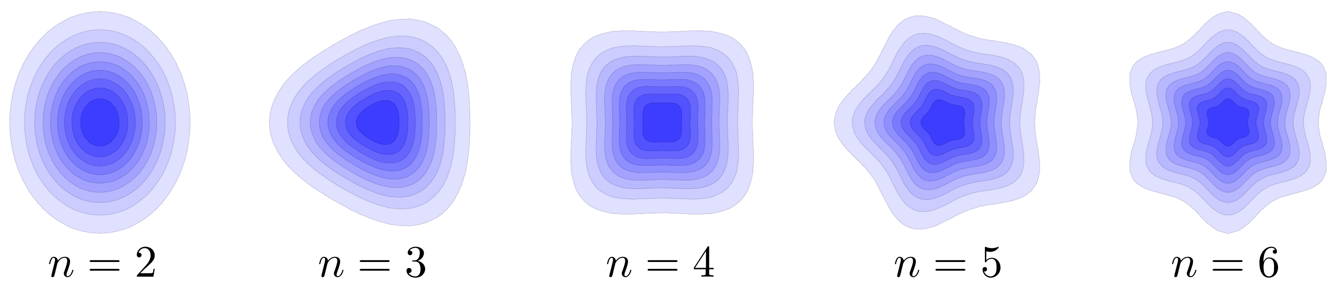


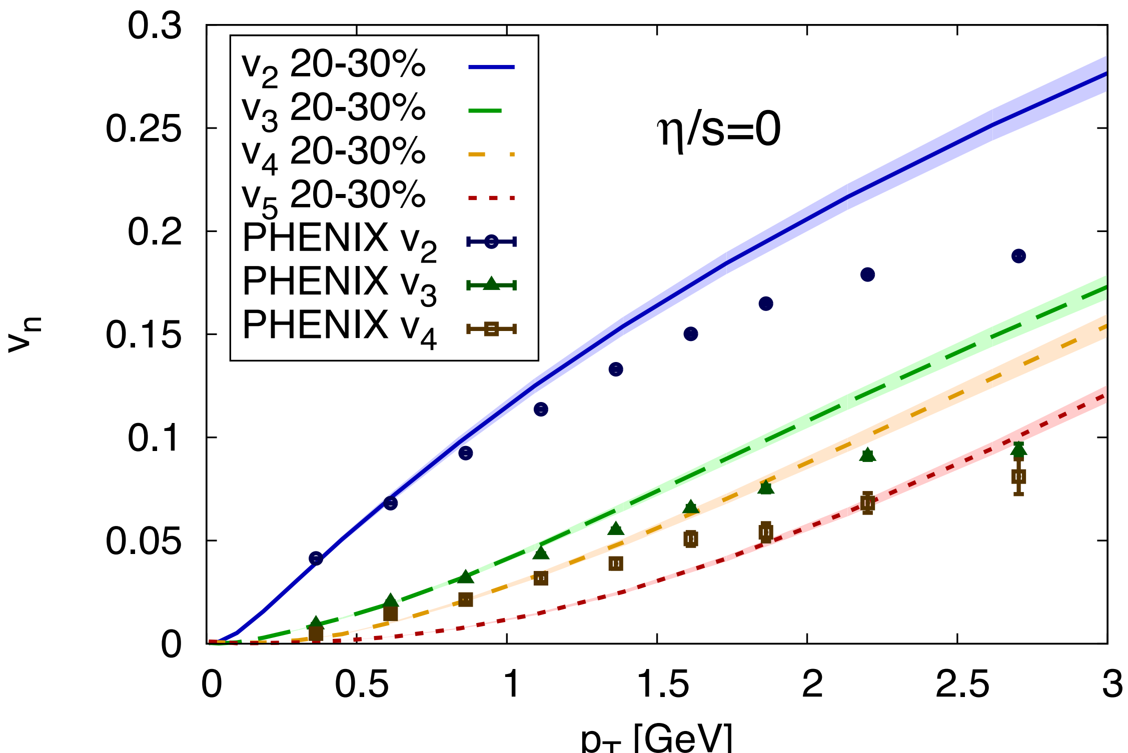


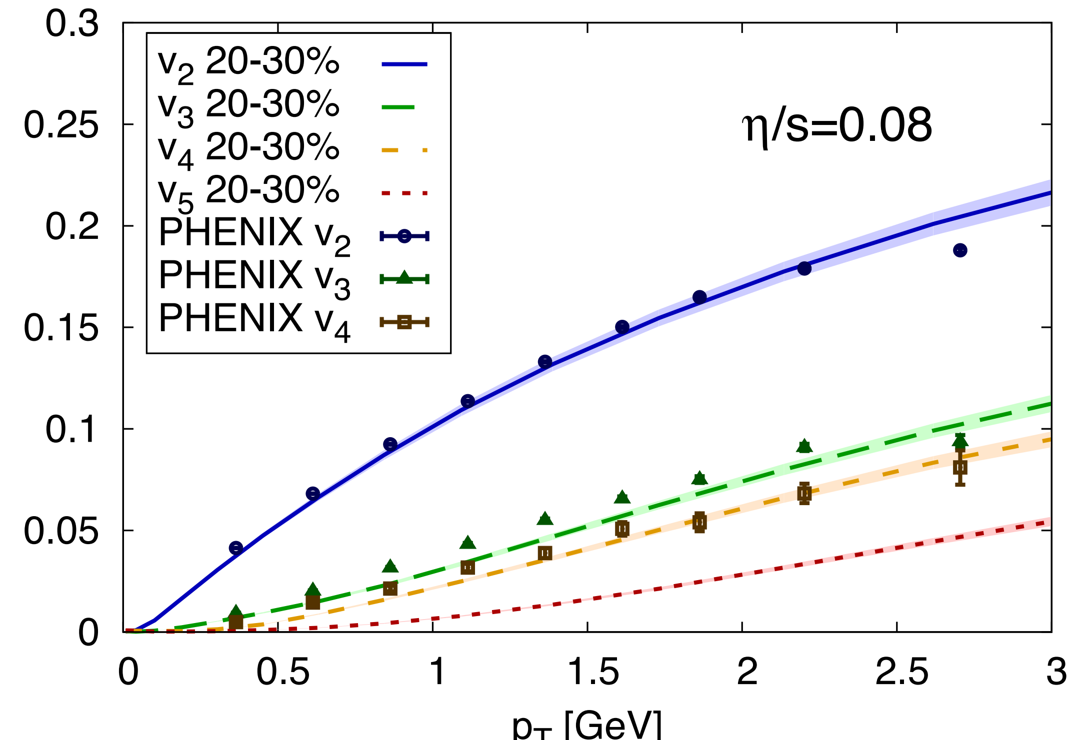


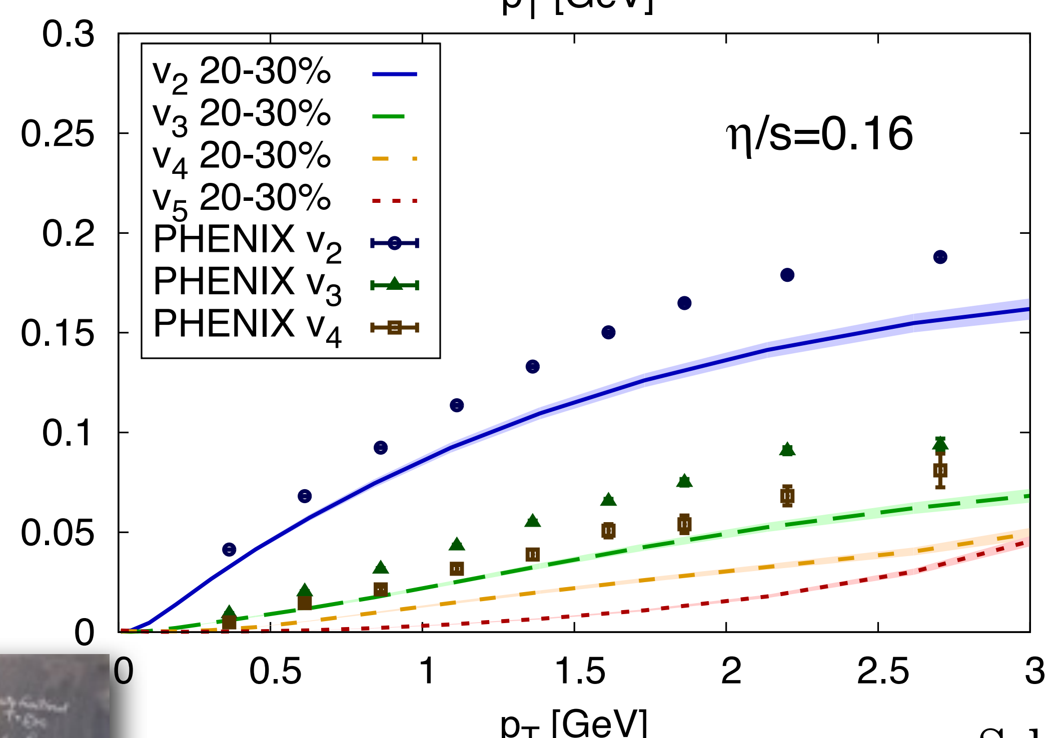
Charles Gale

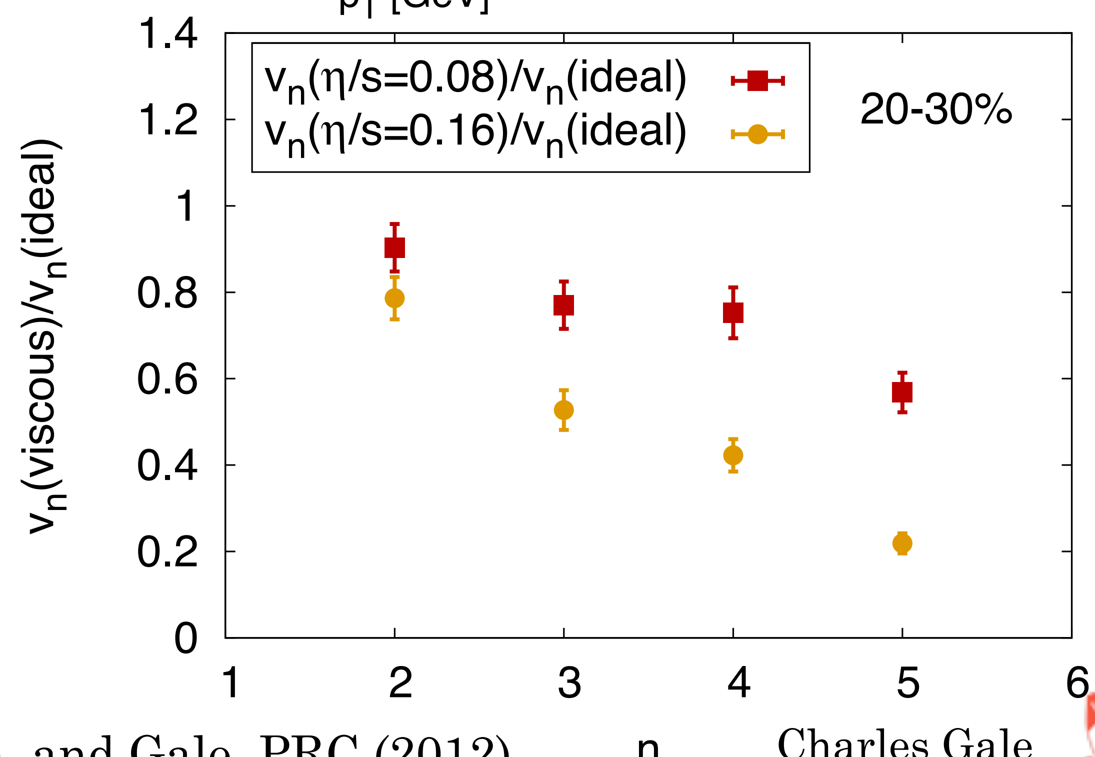
MOVING INTO THE "CHARACTERIZATION" PHASE...







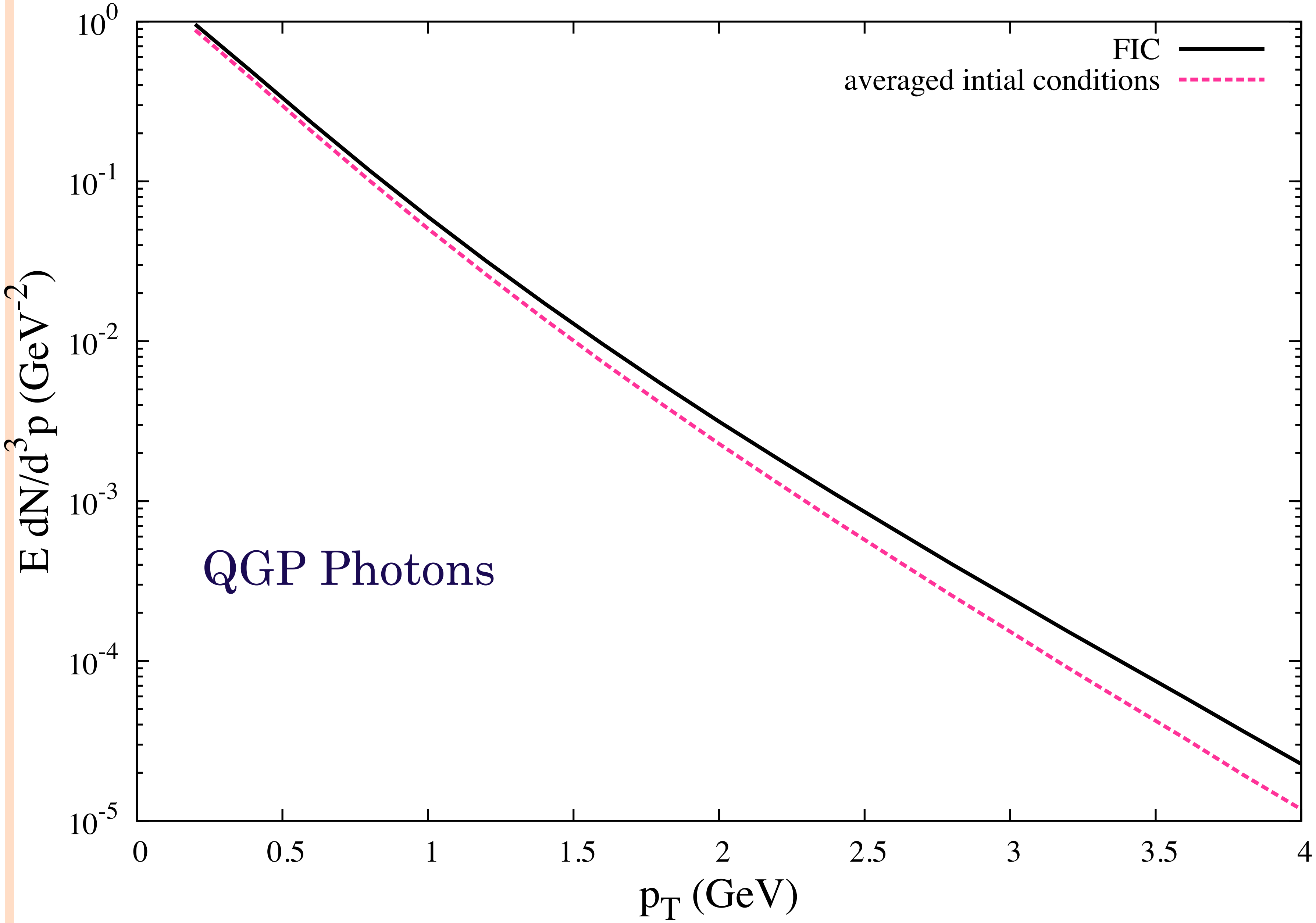




Schenke, Jeon, and Gale, PRC (2012)

Charles Gale

The effect of FIC on the thermal photon spectrum



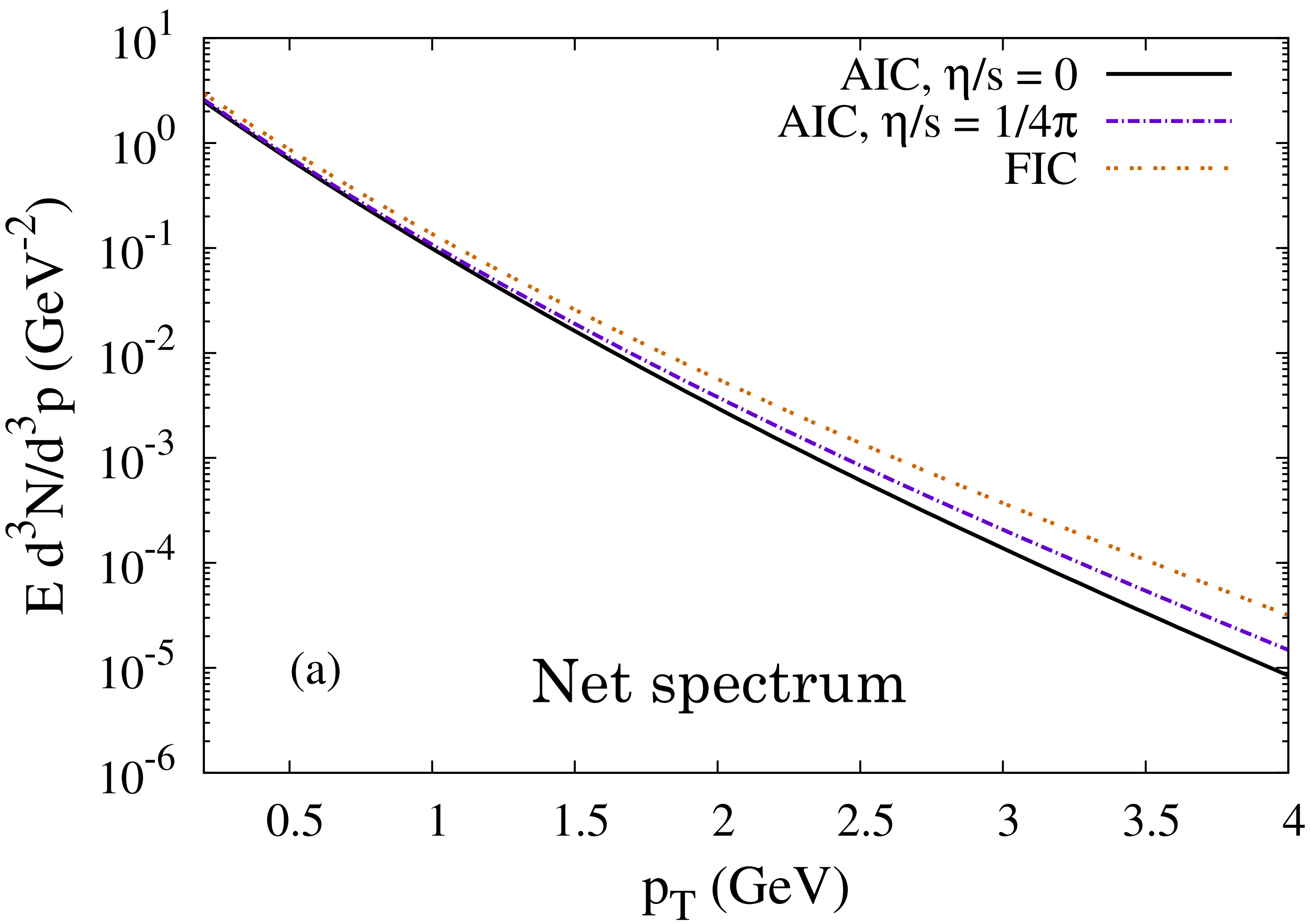
- FIC produces higher initial T (hot spots), and higher initial gradients
- FIC conditions are demanded by hadronic data (v_{odd})
- These lead to a harder spectrum, *as for hadrons*

Dion et al., PRC (2011)
Chatterjee et al., PRC (2011)

All together: FIC + viscosity

- Combined with viscous corrections, FIC yield an enhancement by ≈5 @ 4 GeV, and ≈2 @ 2 GeV
- Temperature estimated by slopes can vary considerably
- A combination of hot spots and blue shift hardens spectra
- Once pQCD photons are included: only modest changes

All together: FIC + viscosity



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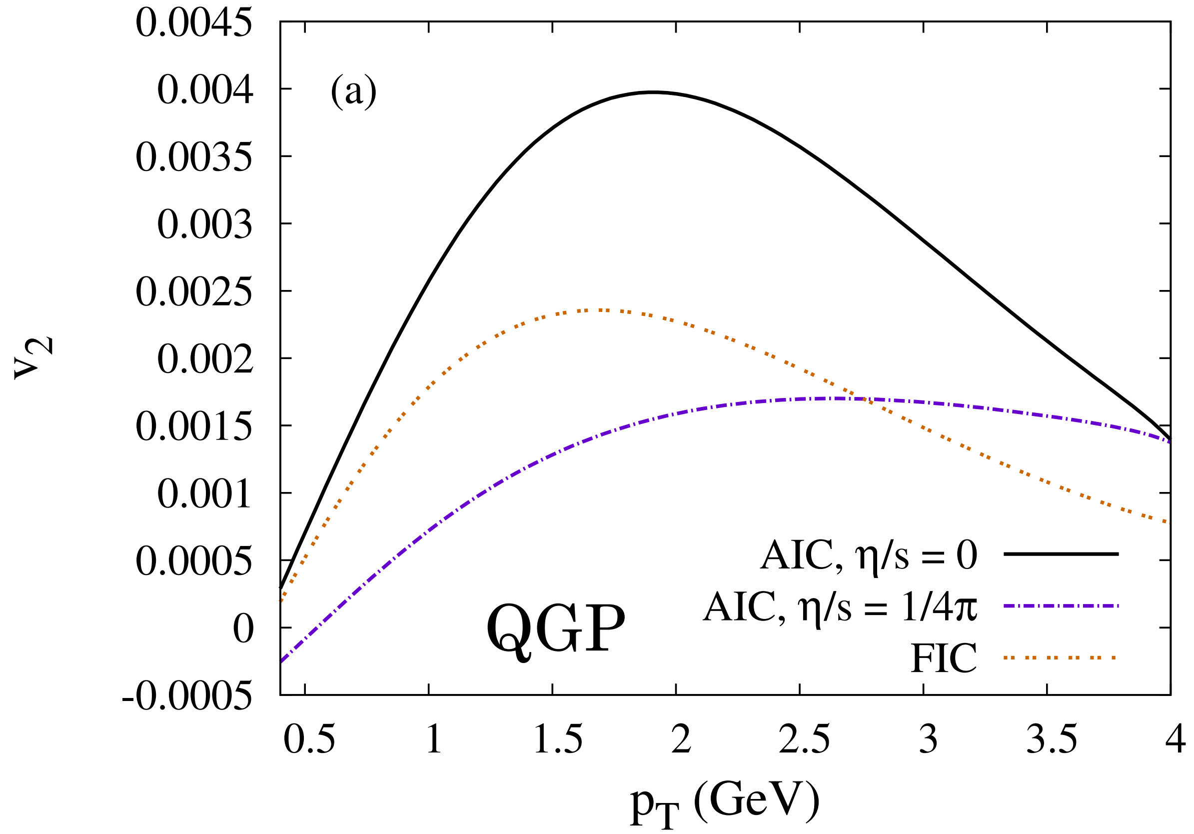
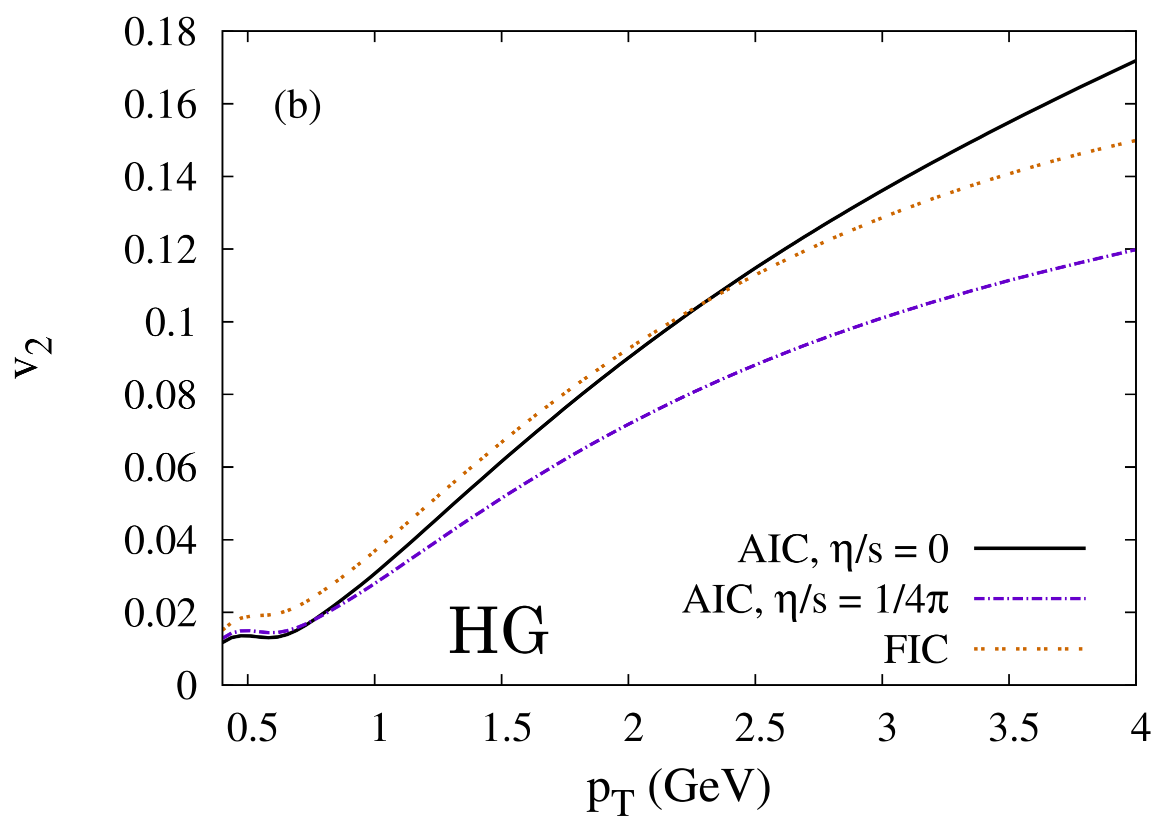
PROGRESS

Charles Gale

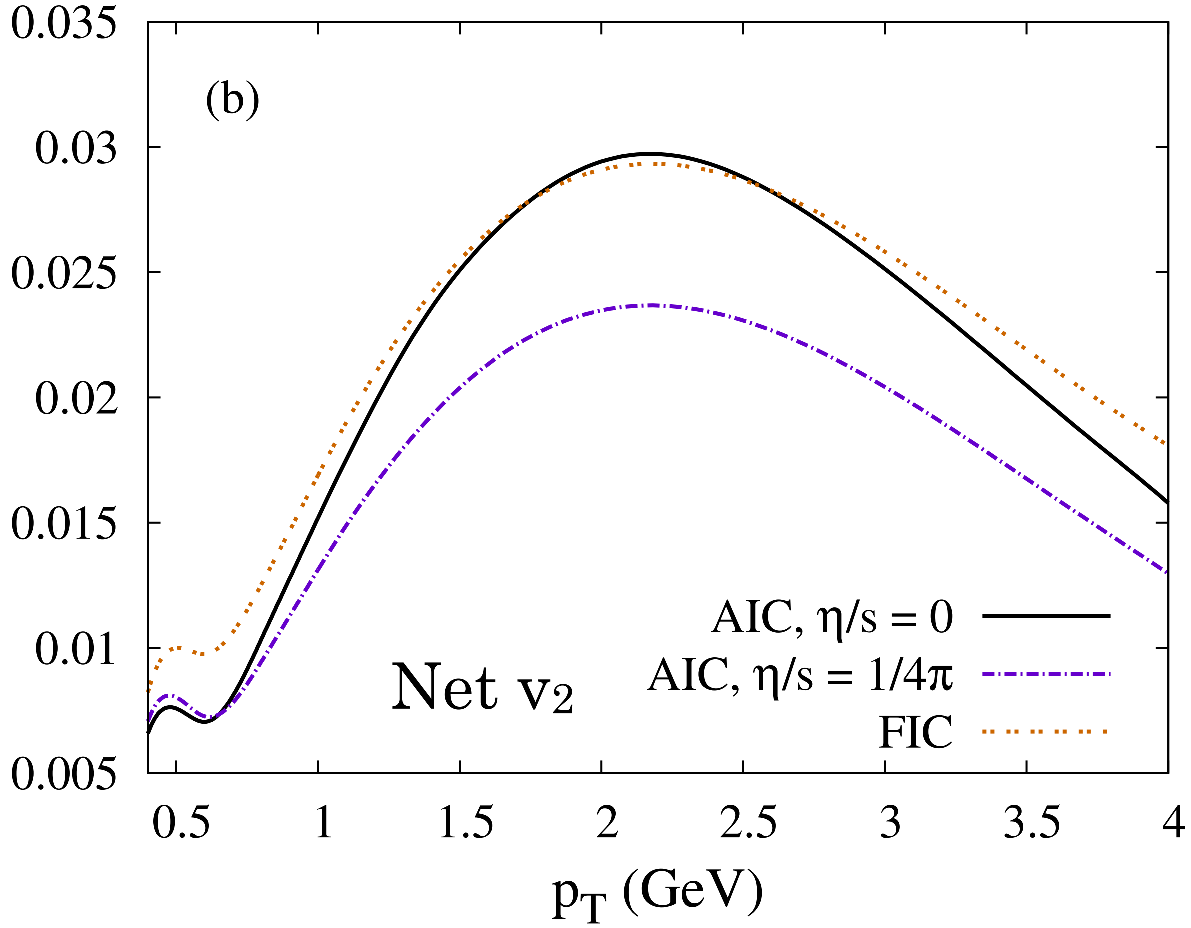
FICs AND THERMAL PHOTON V_2





- FICs enhance v_2 in this centrality class (0-20%), as for hadrons
- For hadrons measured in events belonging to large centrality, FICs will *decrease* v_2
- HG elliptic flow is much larger than QGP elliptic flow, but remember net v_2 is a weighted average

FICs and thermal photon v_2



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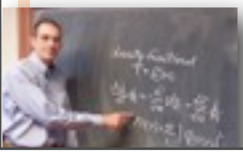
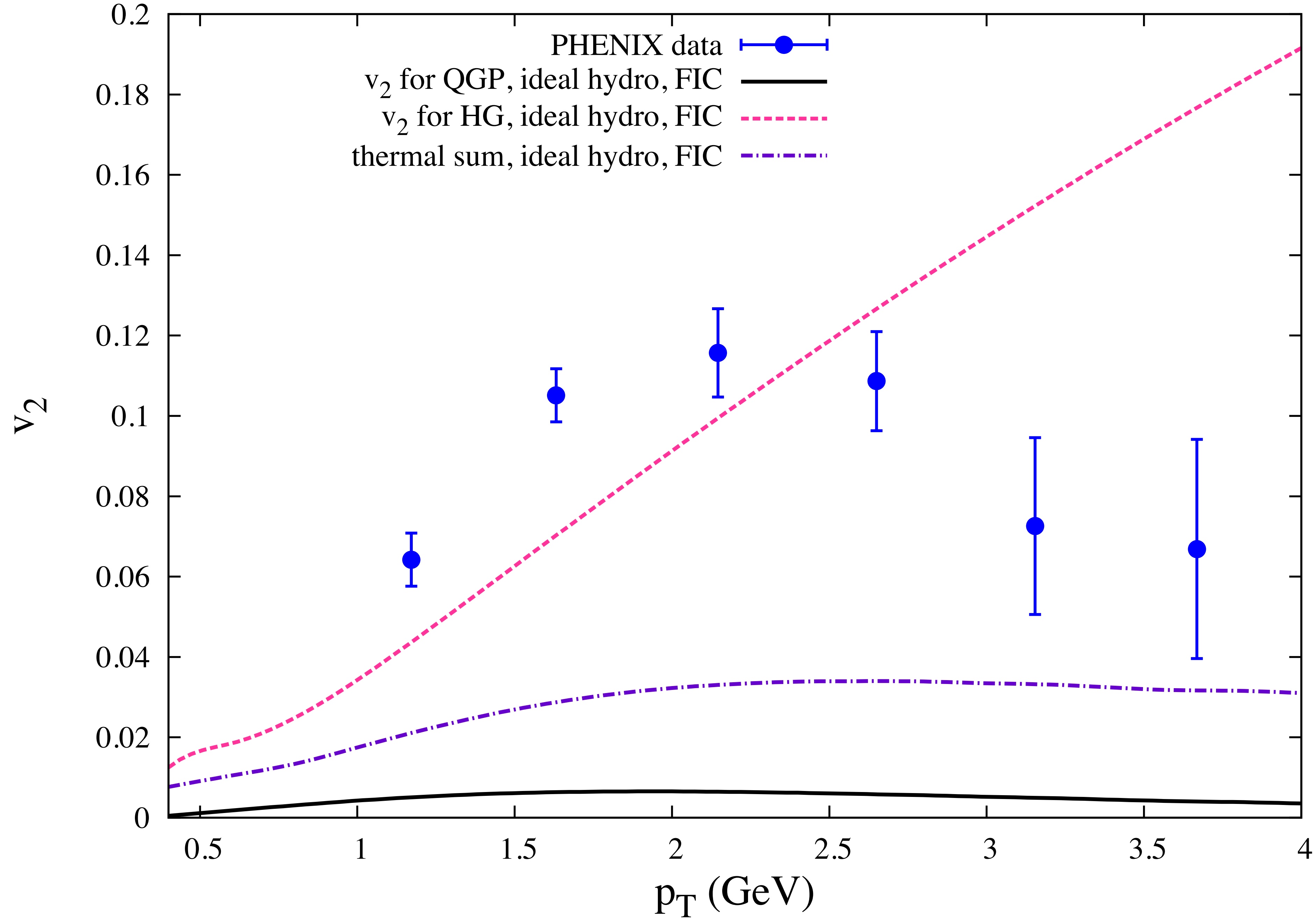
- For hadrons measured in events belonging to large centrality, FICs will *decrease* v_2
- HG elliptic flow is much larger than QGP elliptic flow, but remember net v_2 is a weighted average
- Net v_2 is comparable in size to that with ideal medium.

PROGRESS

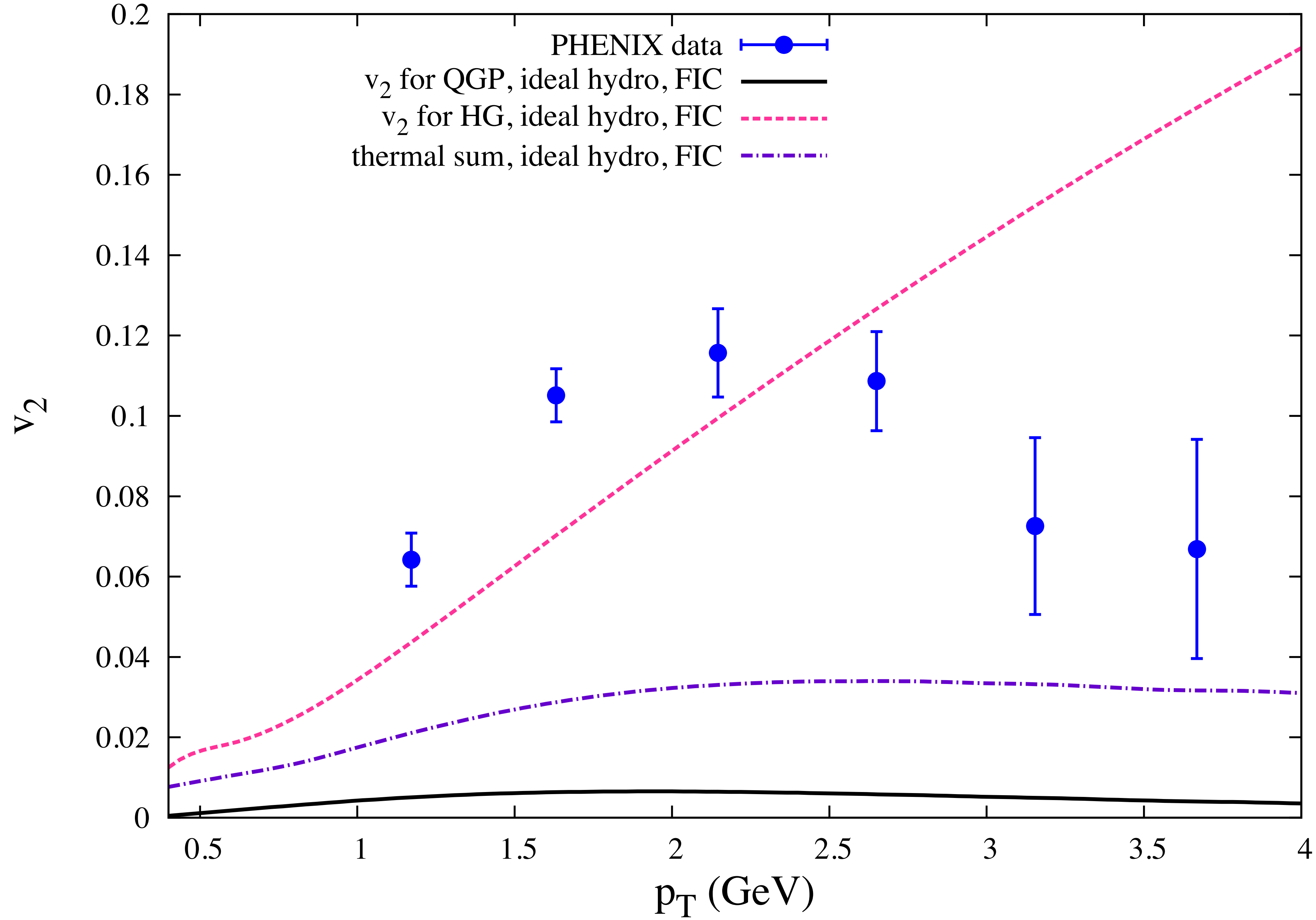


PHOTON v_2 DATA?



- New data is higher than calculation, even with e-b-e initial state fluctuations, and ideal hydro
- Size comparable with HG v_2

Photon v_2 Data?



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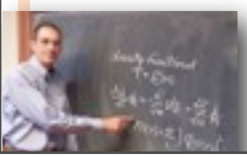
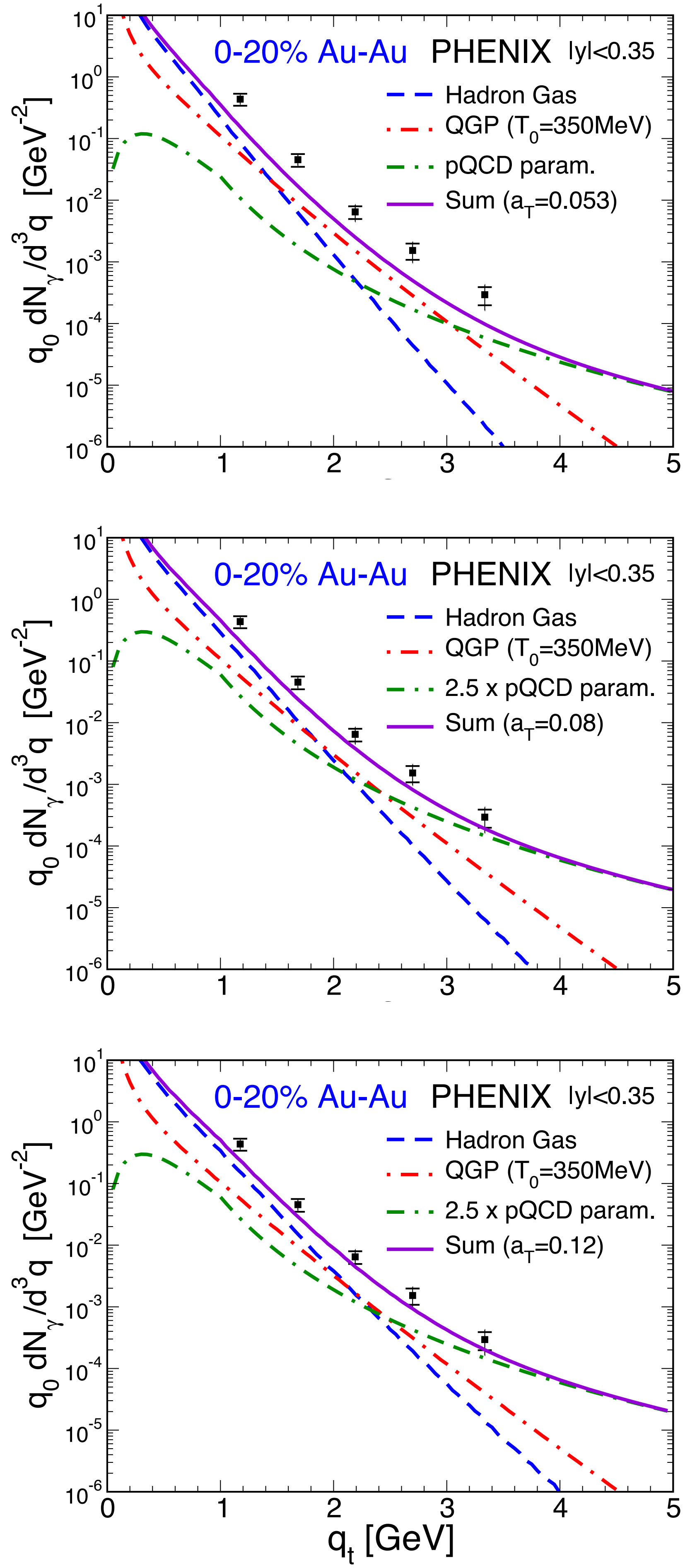
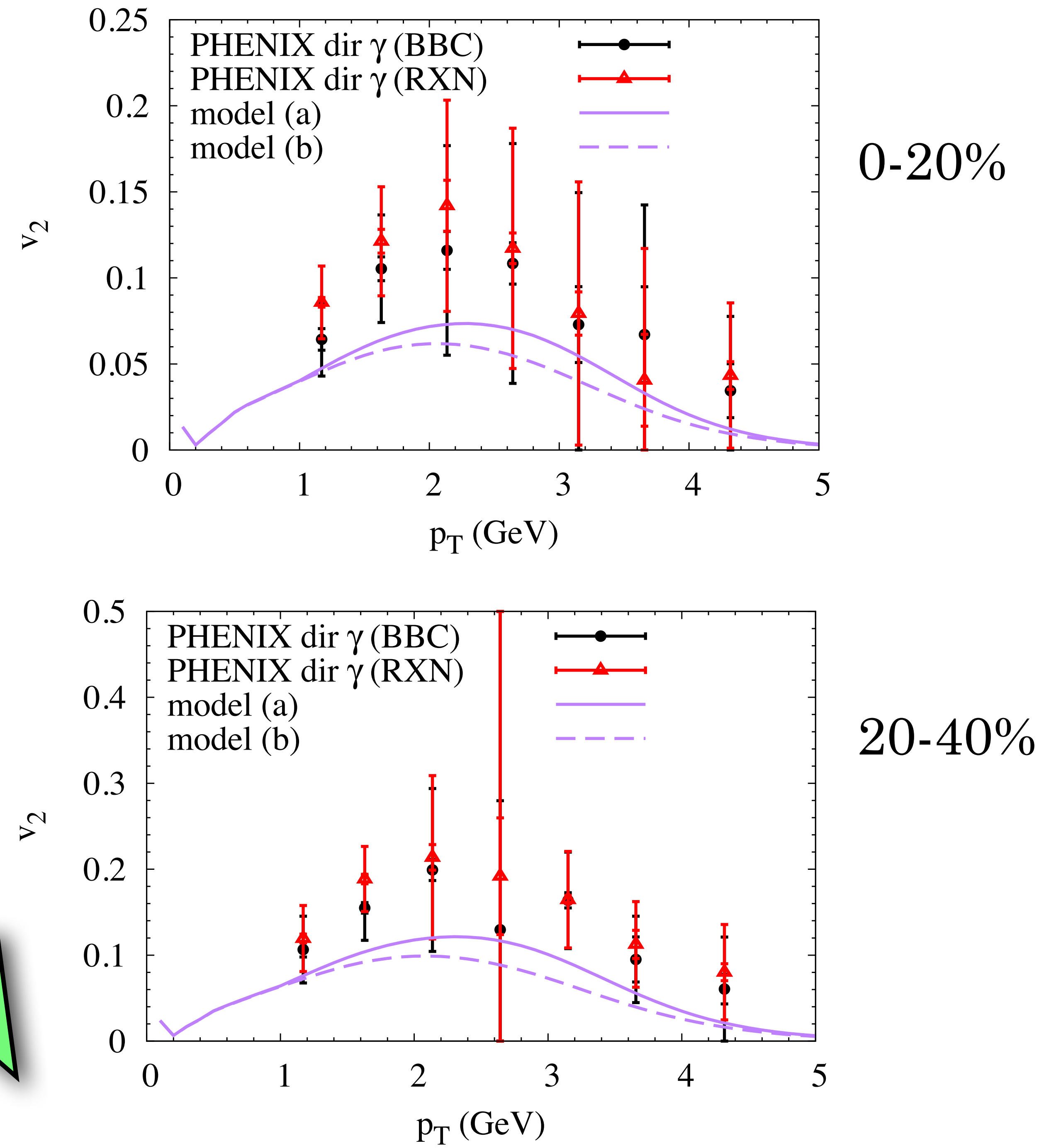


CAN THE DATA TEACH US ABOUT DYNAMICS?





van Hees, Rapp, Gale PRC (2011)

Charles Gale

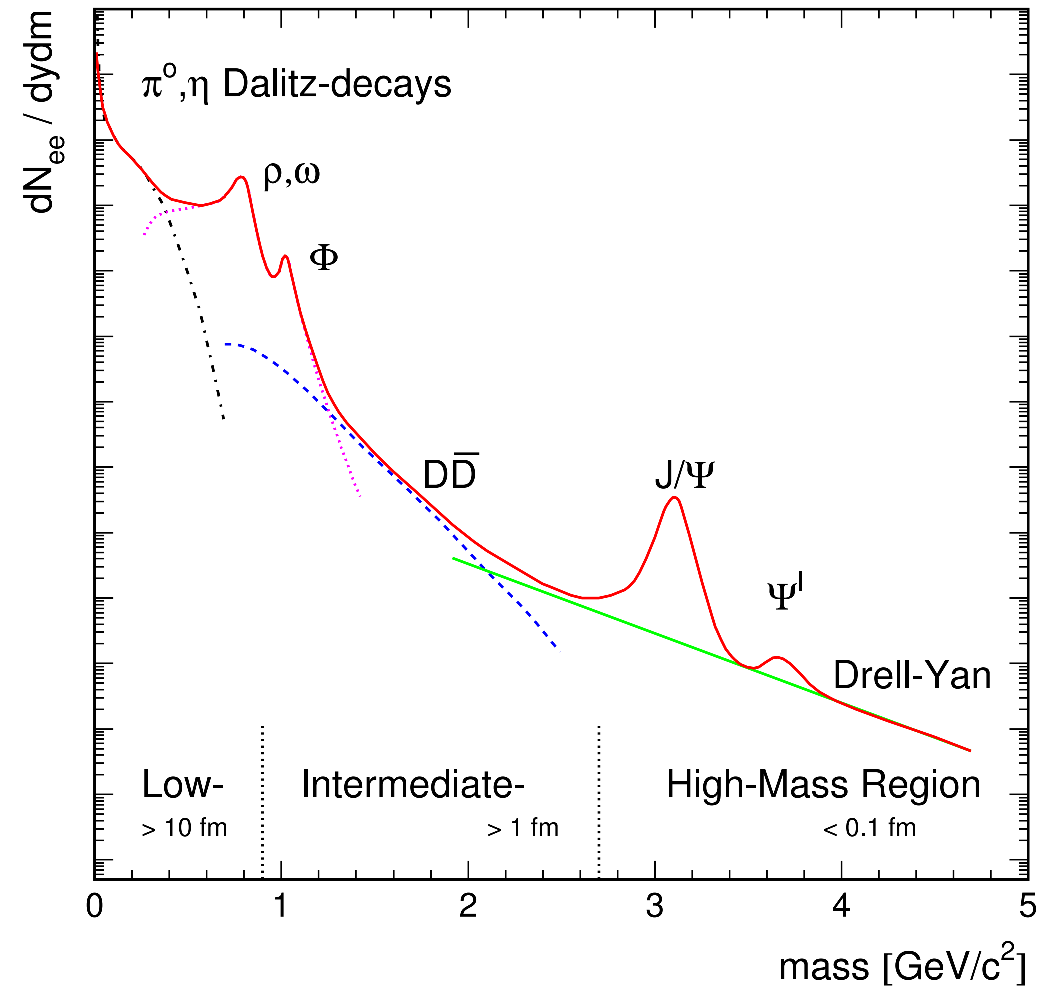
Some facts and some leads

- FICs are here to stay. The meaning of “initial temperature” is altered.
- Need to explore hydro initialization and parameters. This requires consistency with the hadronic data.
- Making the QGP signal larger will *decrease* the v_2. Including the T=0 photons, will *decrease* v_2.
- Non-zero initial shear tensor? Primordial flow?

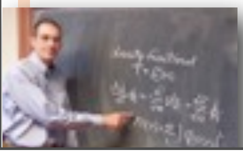
What about dileptons?
Thermal dilepton spectrum, and elliptic flow

$$v_2(M, p_T, b) = \frac{\int d\phi \cos(2\phi) \frac{d^4N}{dM^2 dy\, p_T dp_T d\phi}}{\int d\phi \frac{d^4N}{dM^2 dy\, p_T dp_T d\phi}}$$

Chatterjee, Srivastava, Heinz, Gale, PRC (2007)

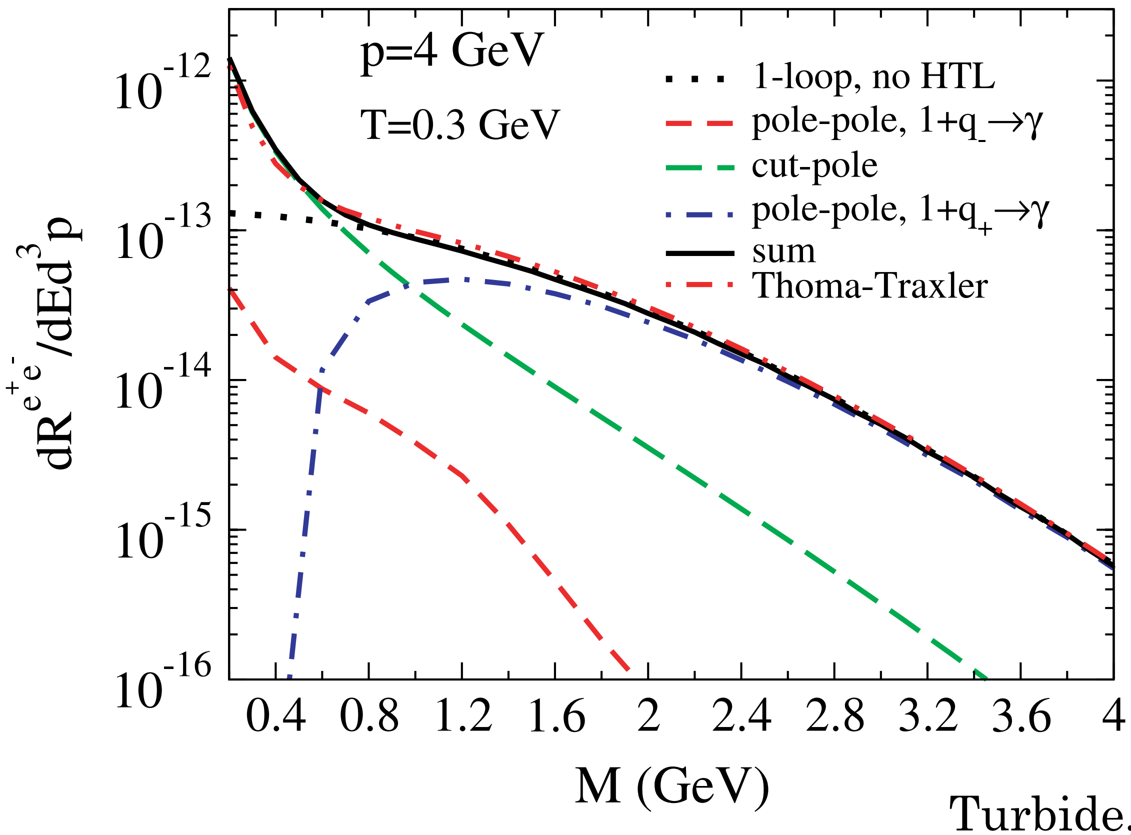


- Additional degree of freedom: M and p_T may be varied independently



THERMAL DILEPTON SOURCES, QGP

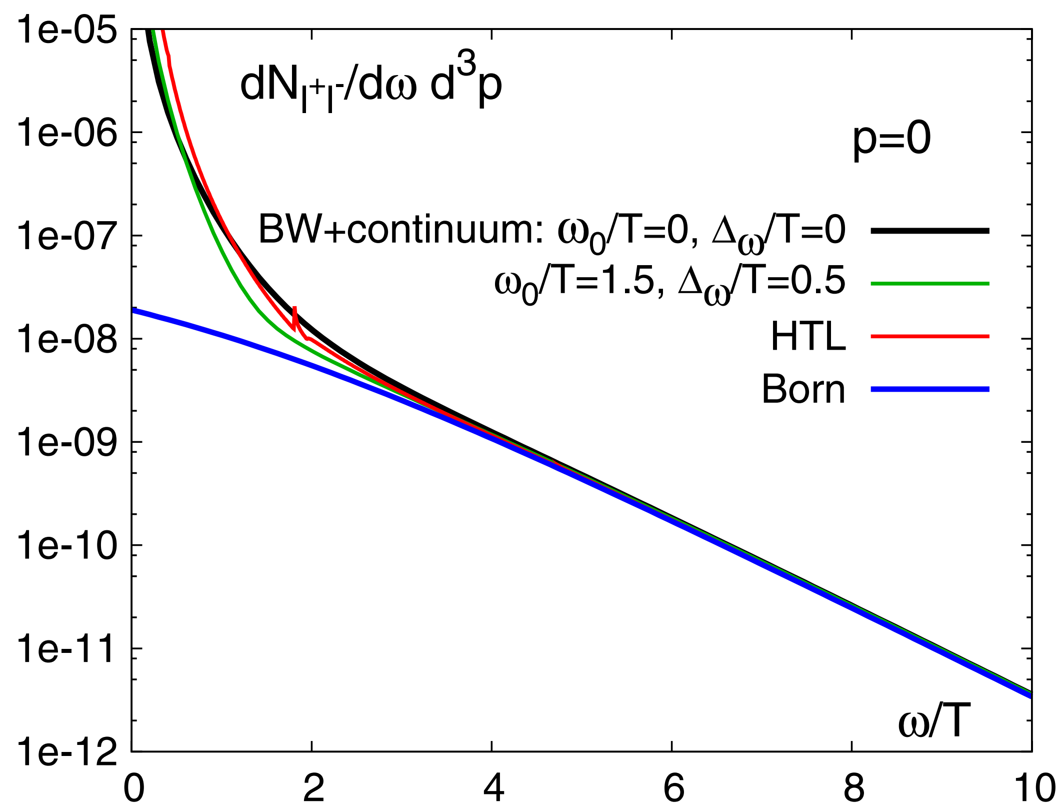
- HTL at finite momentum:



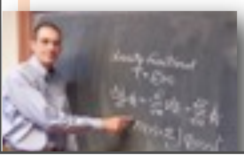
Turbide, Gale, Srivastava, Fries PRC (2006)

- Non-perturbative estimate:

∴ No single calculation covers the entire dilepton kinematical phase space



Ding et al., PRD (2011)



Thermal dilepton sources, QGP

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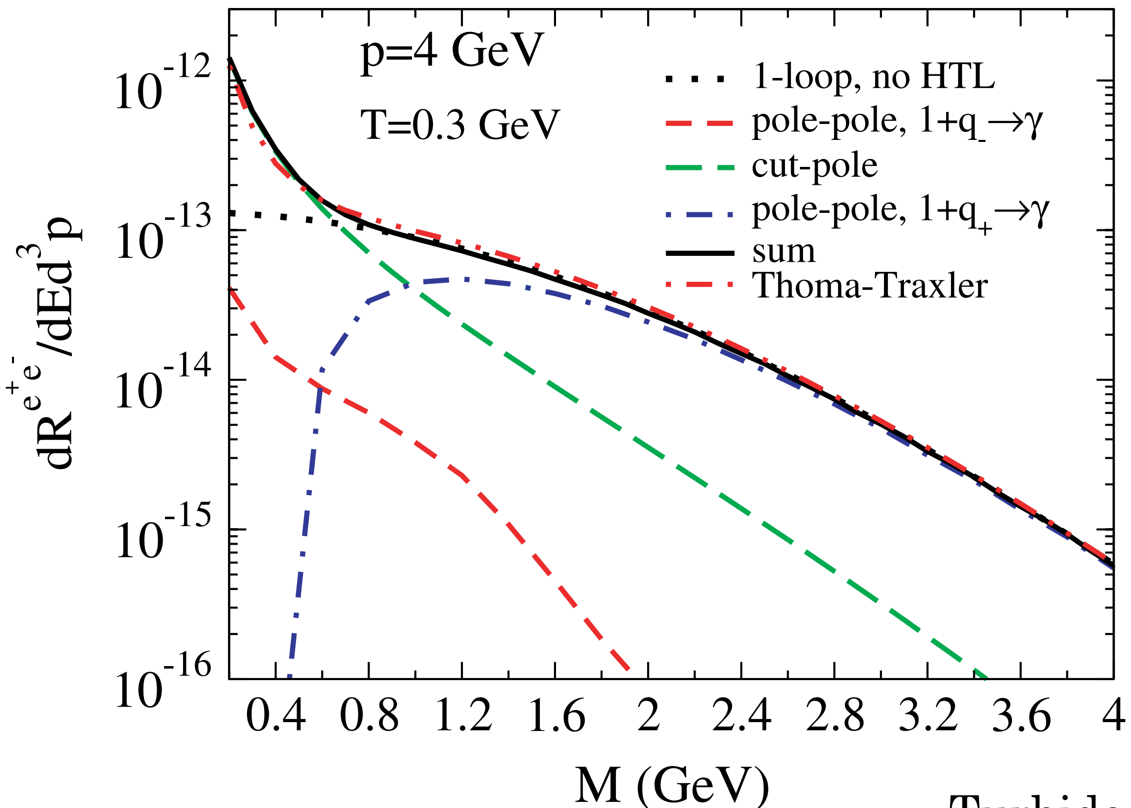
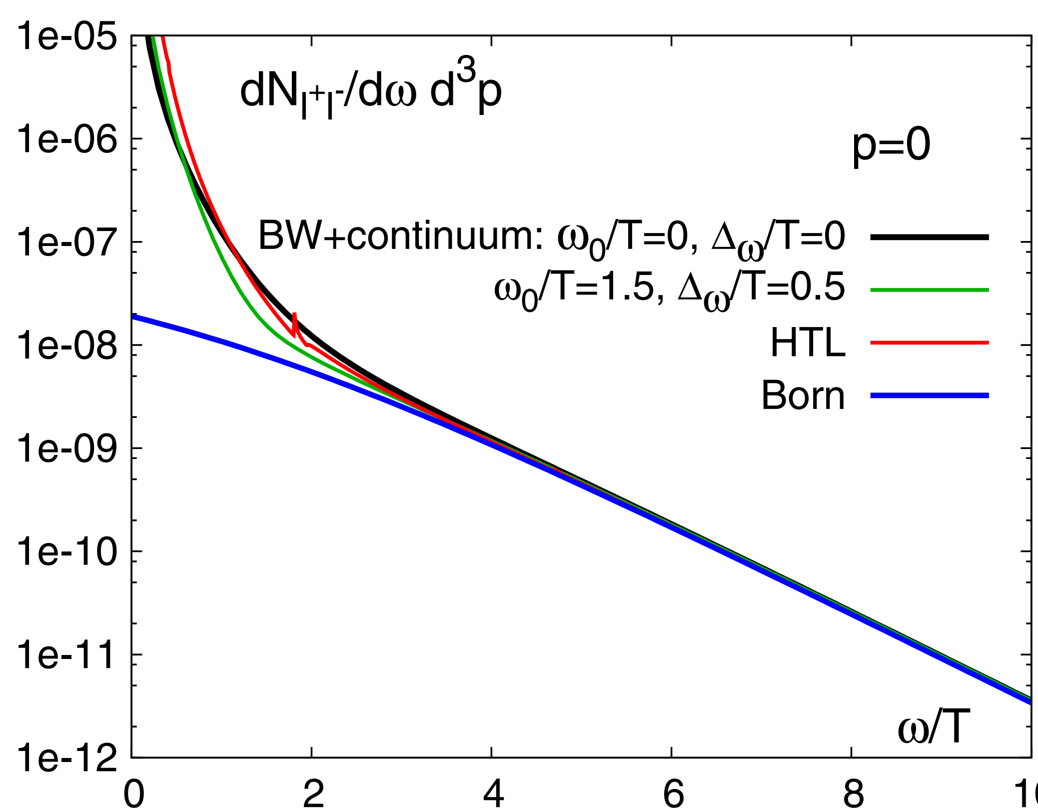


Turbide, Gale, Srivastava, Fries PRC (2006)

- Non-perturbative estimate:

$\therefore$ No single calculation covers the entire dilepton kinematical phase space



Ding et al., PRD (2011)

PROGRESS

Thermal dilepton sources, HG

- HG contribution: calculate the in-medium vector spectral density

  - Many-Body approach with hadronic effective Lagrangians
    - Rapp and Wambach, ANP (2000)

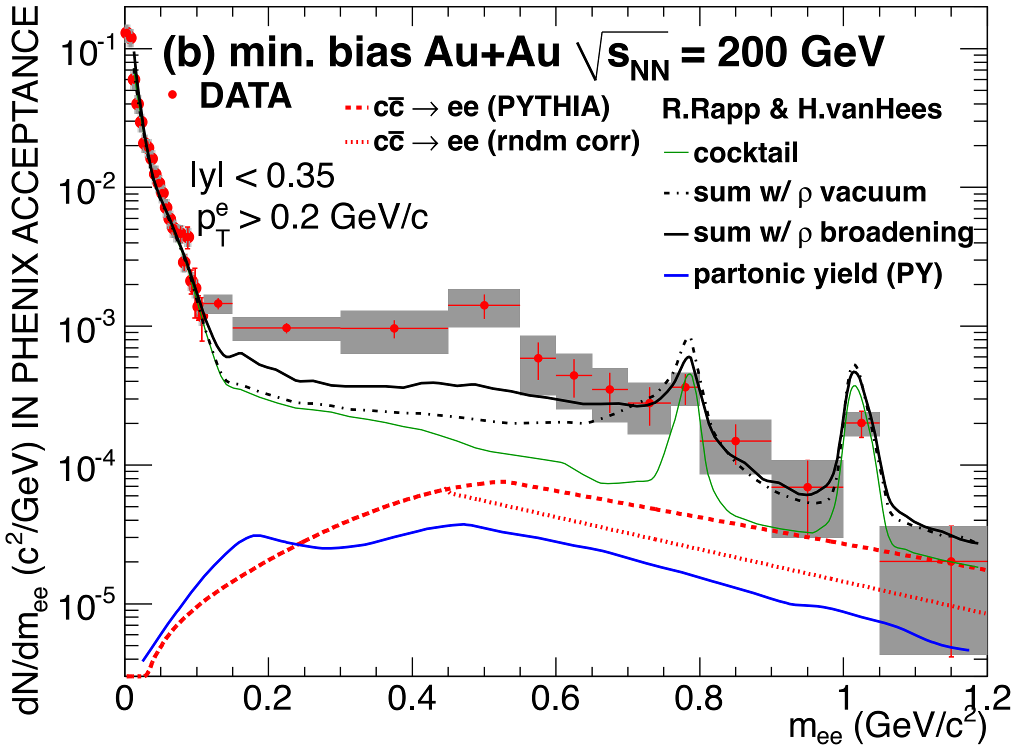
  - Empirical evaluation of the vector mesons forward-scattering amplitudes

$$\Pi_{ab}(E,p) = -4\pi \int \frac{d^3k}{(2\pi)^3} n_b(\omega) \frac{\sqrt{s}}{\omega} f_{ab}^{\text{c.m.}}(s)$$

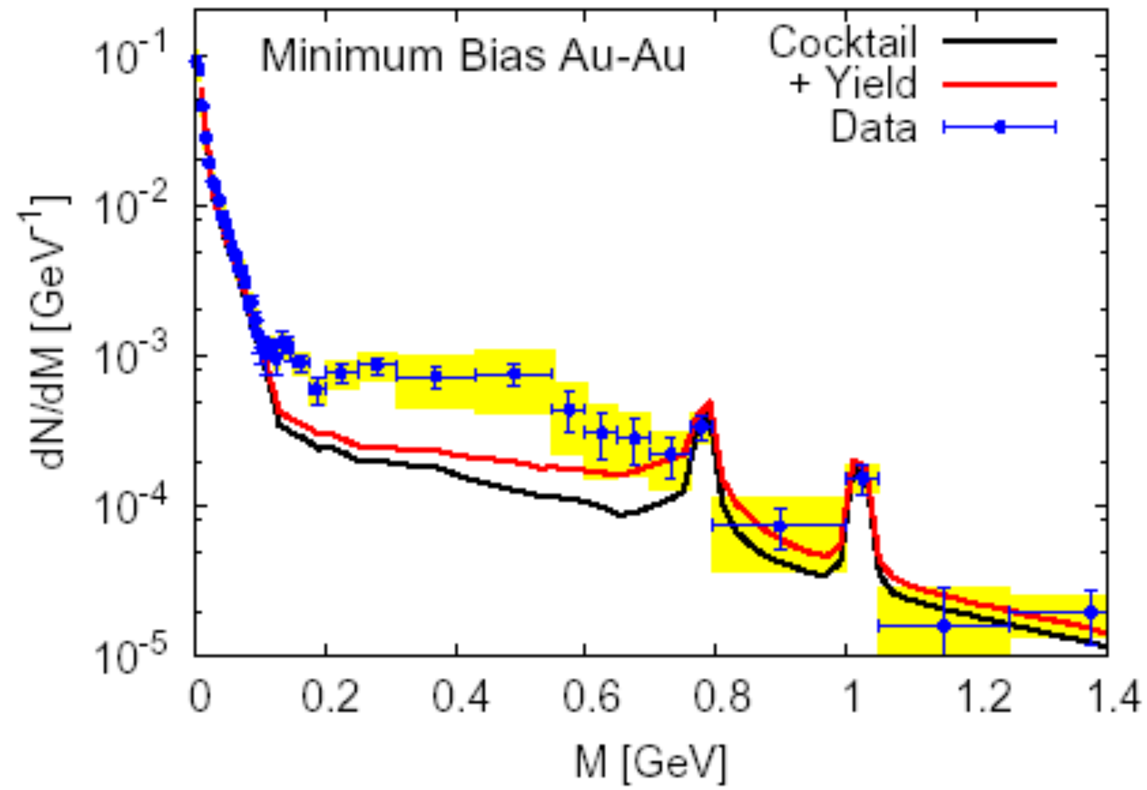
    - E. Shuryak, NPA (1991)
    - Eletsky, Ioffe, Kapusta (1999)
    - Vujanovic, Gale (2009)

  - Chiral Reduction formulae
    - Yamagishi, Zahed (1996)

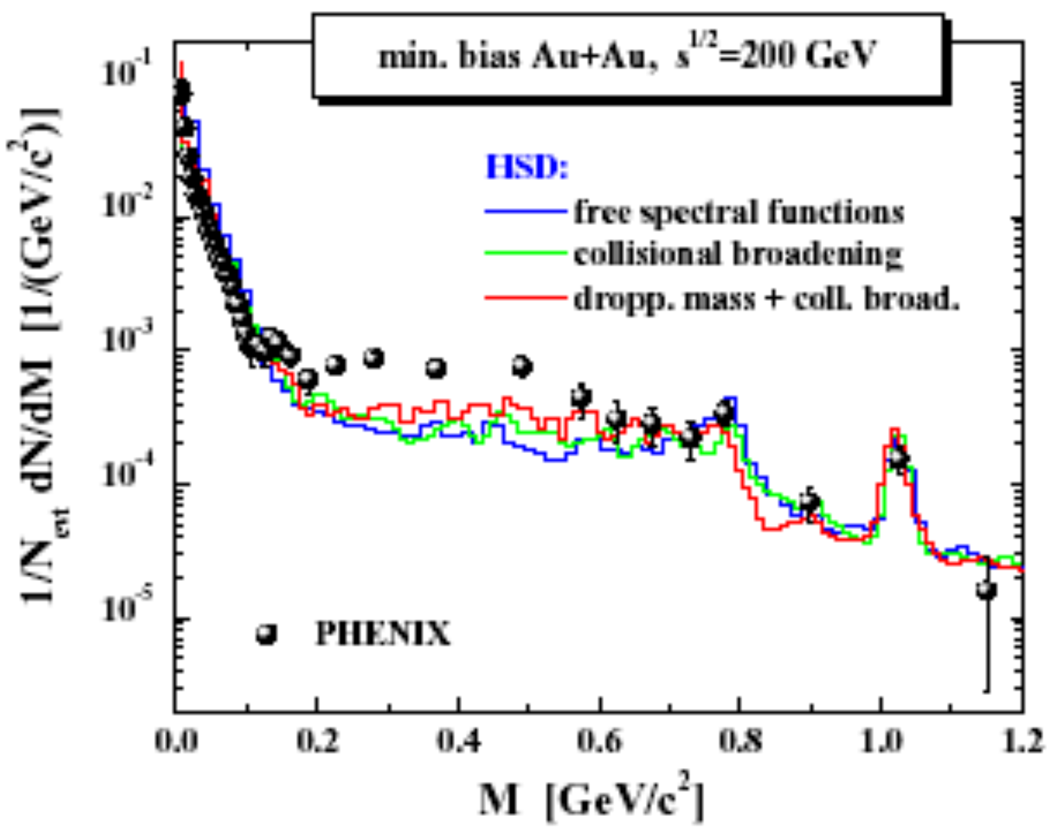
DILEPTONS, THE STORY AS OF A FEW MONTHS AGO



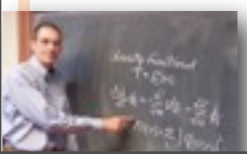
van Hees, Rapp (2010)



Dusling, Zahed (2009)



Bratkovskaya, Cassing, Linnyk (2012)



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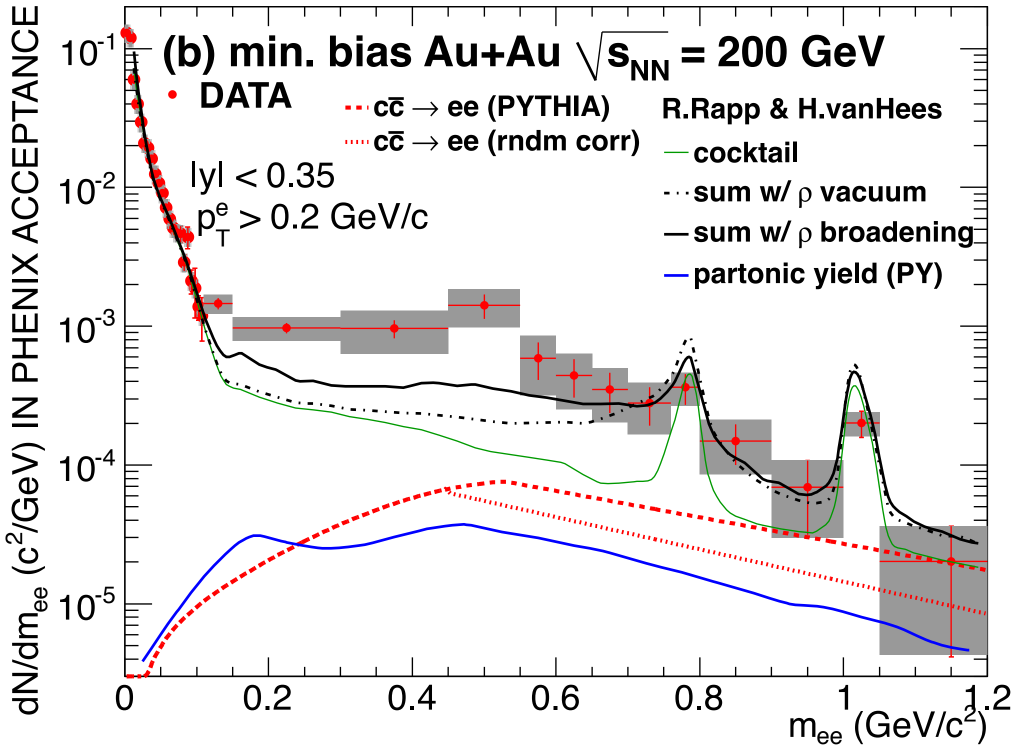
DILEPTONS, THE STORY AS OF A FEW MONTHS AGO



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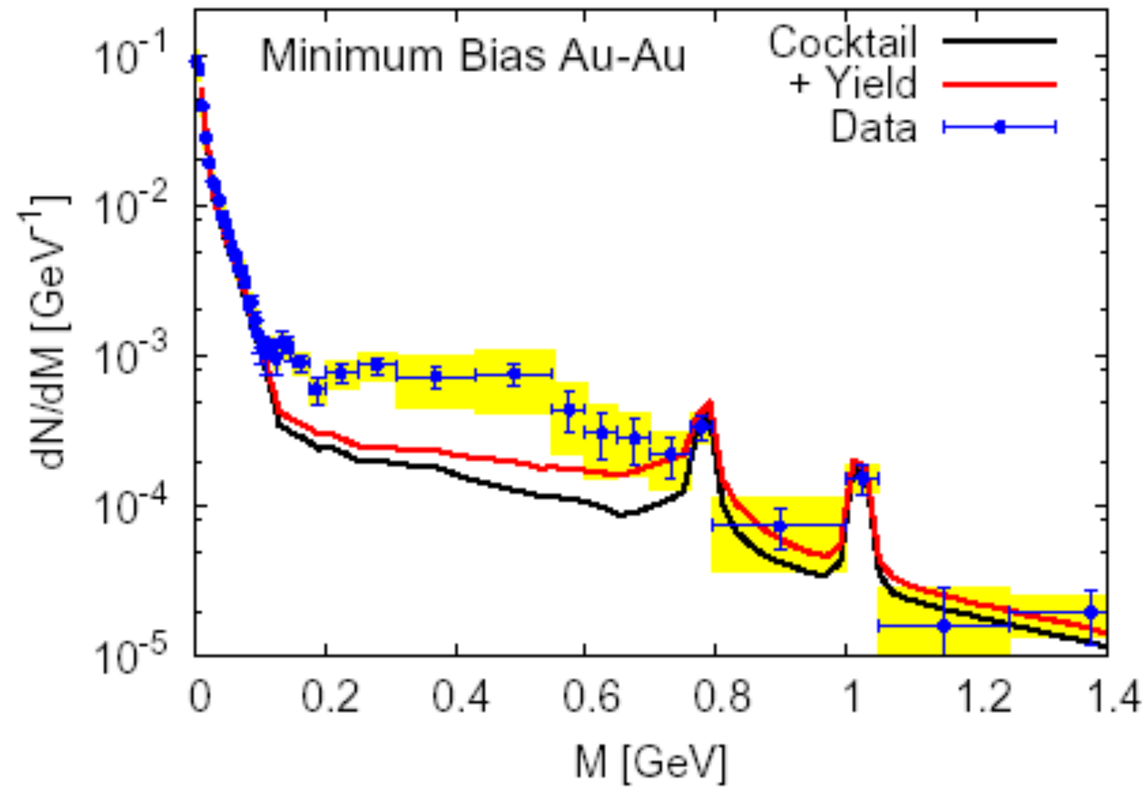
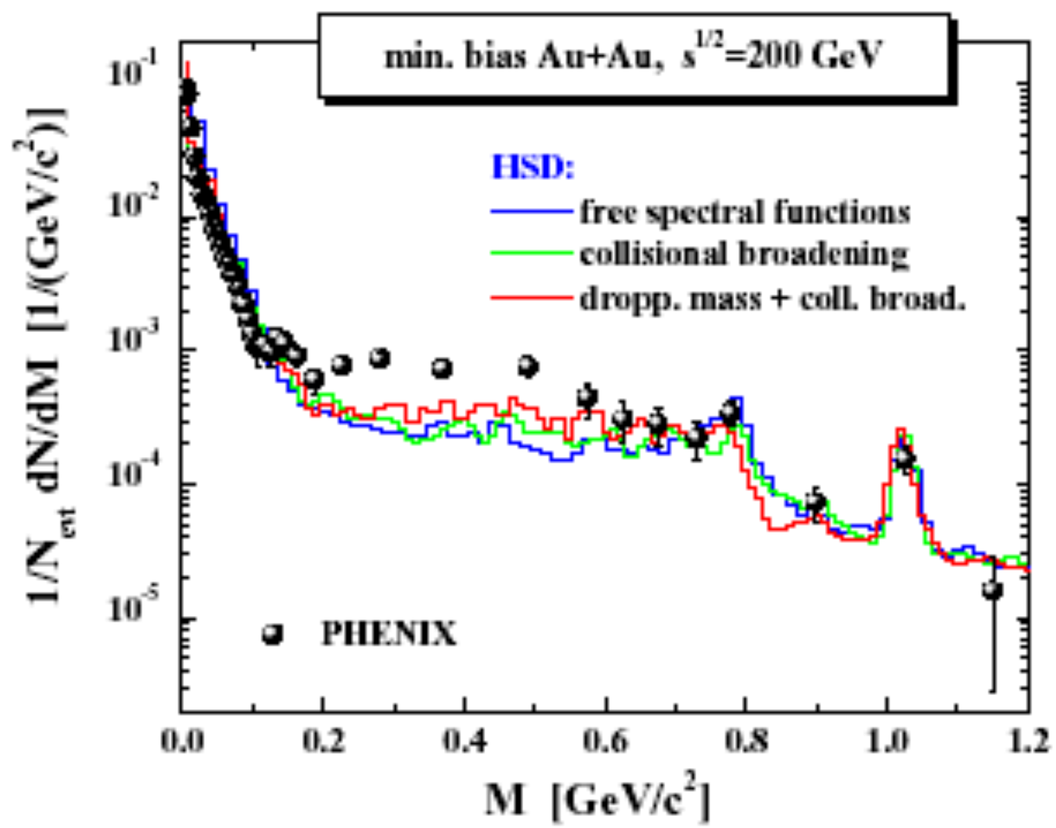


Dusling, Zahed (2009)



Bratkovskaya, Cassing, Linnyk (2012)

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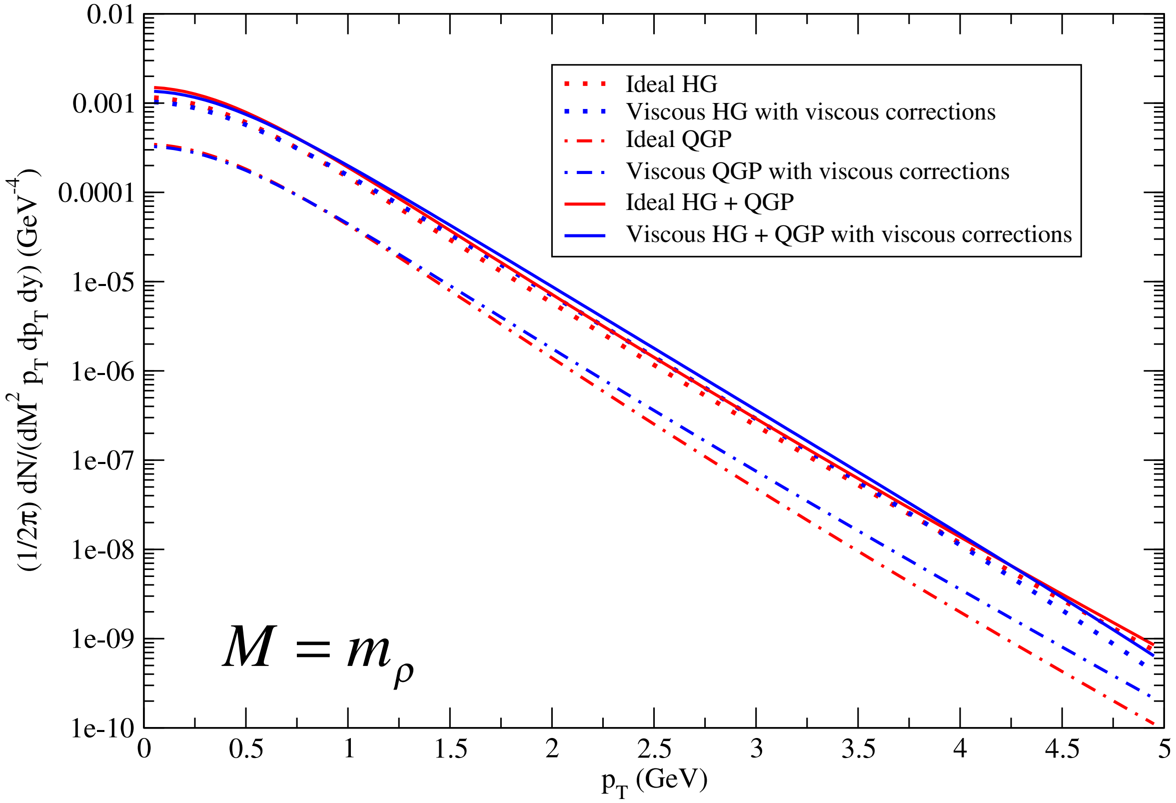
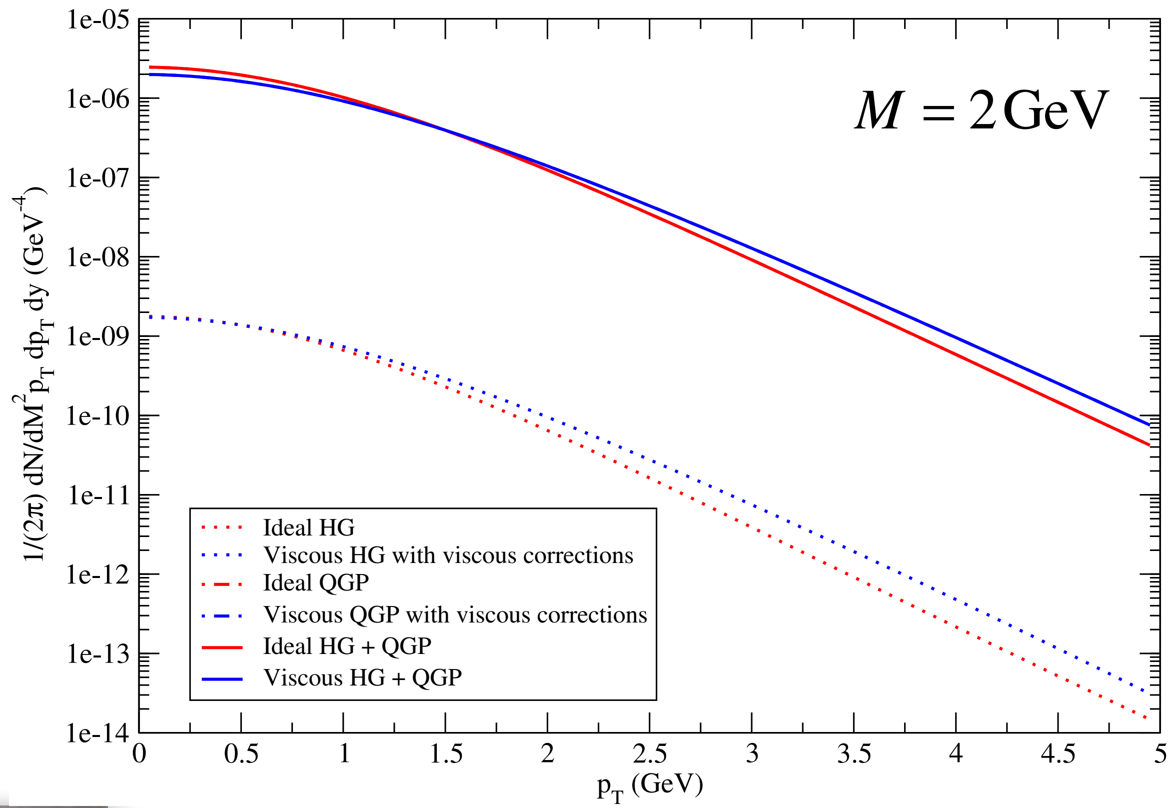
THERMAL DILEPTON SPECTRA: VISCOSITY?

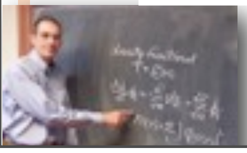




- Transition from HG-dominated to QGP-dominated
- Charm not included here
- Effects of viscous corrections are modest

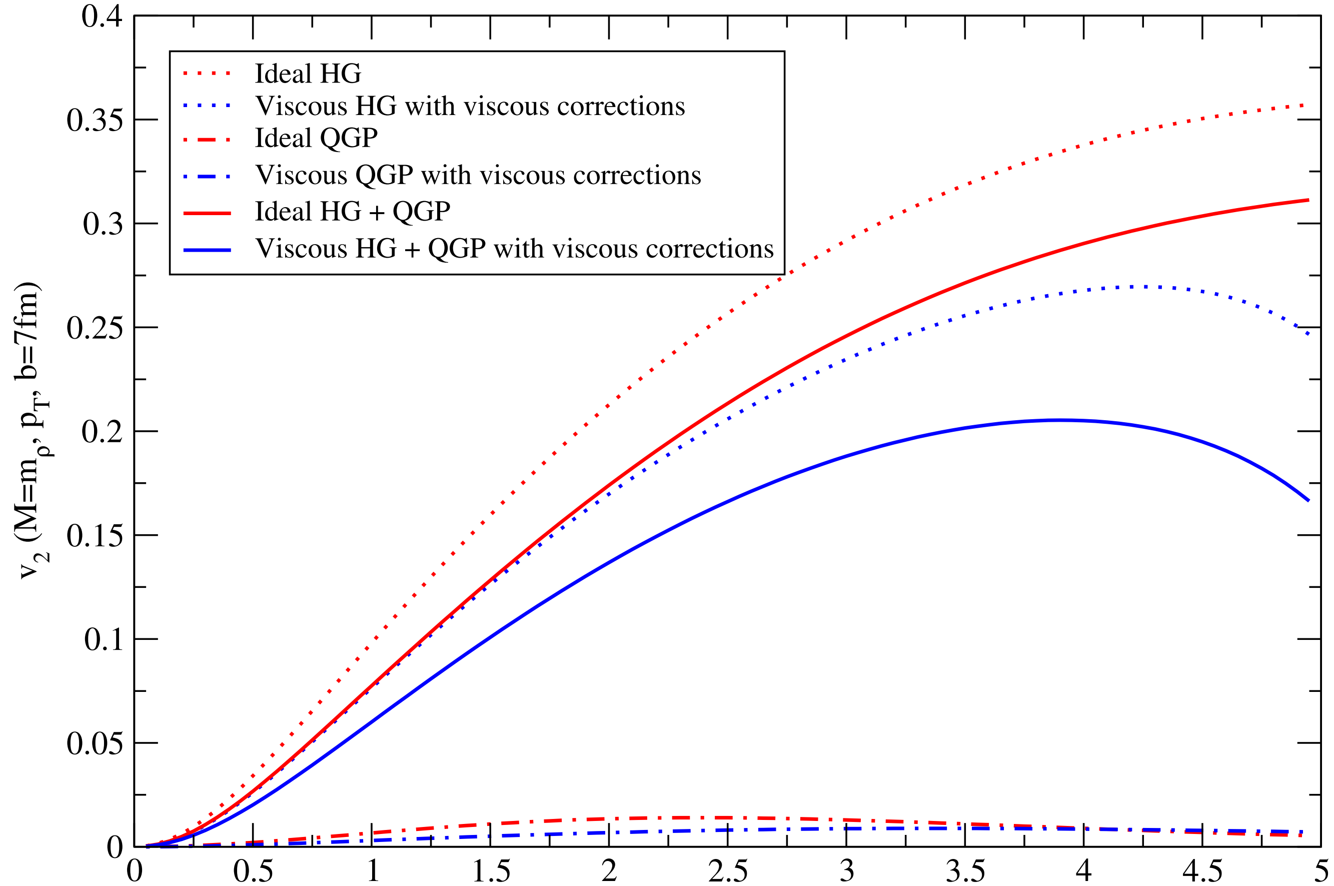
  Dusling & Lin, NPA (2008)

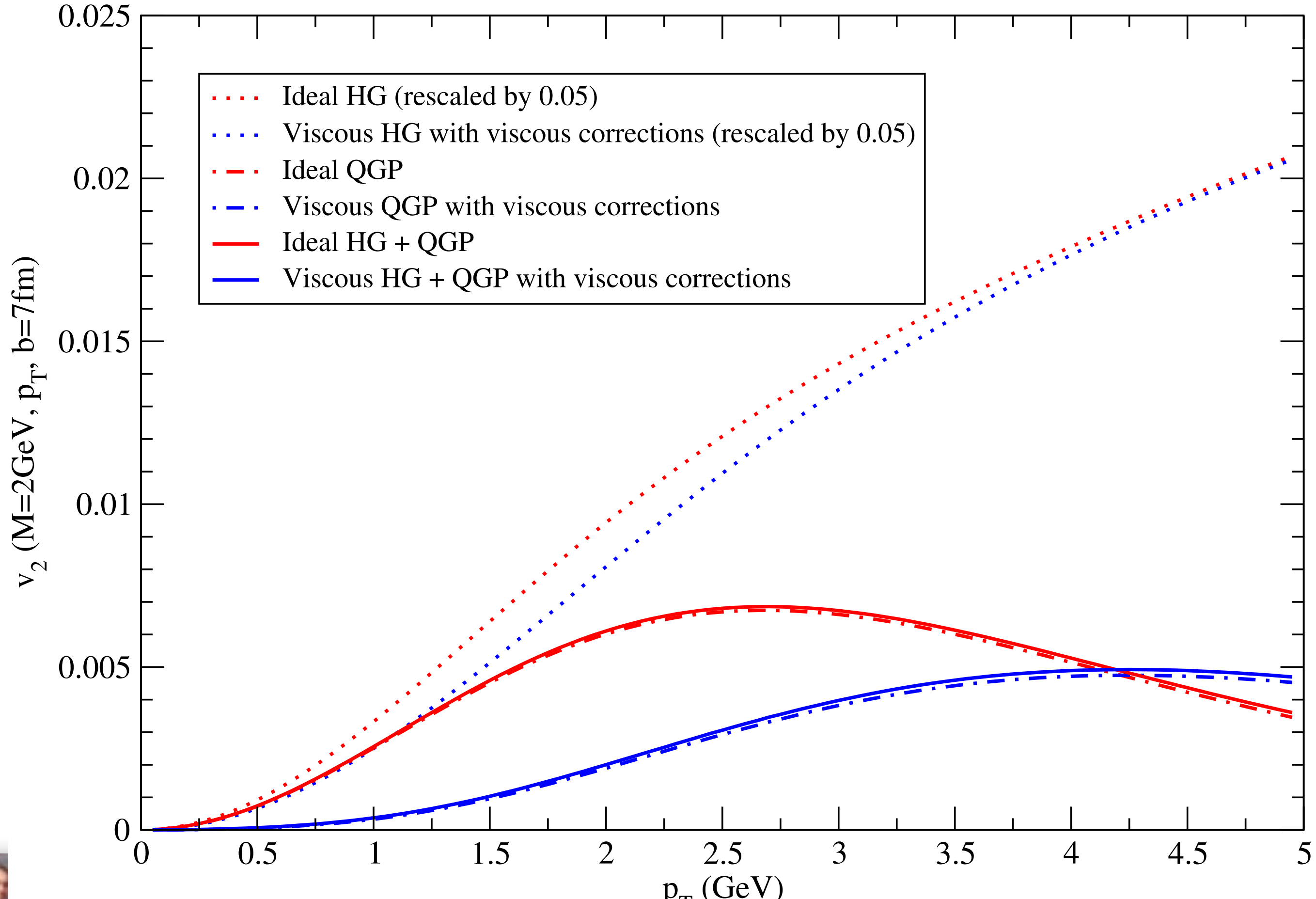
- Same hydro as for photon calculations



G. Vujanovic, 2011-12

Thermal dilepton v_2 with viscous effects





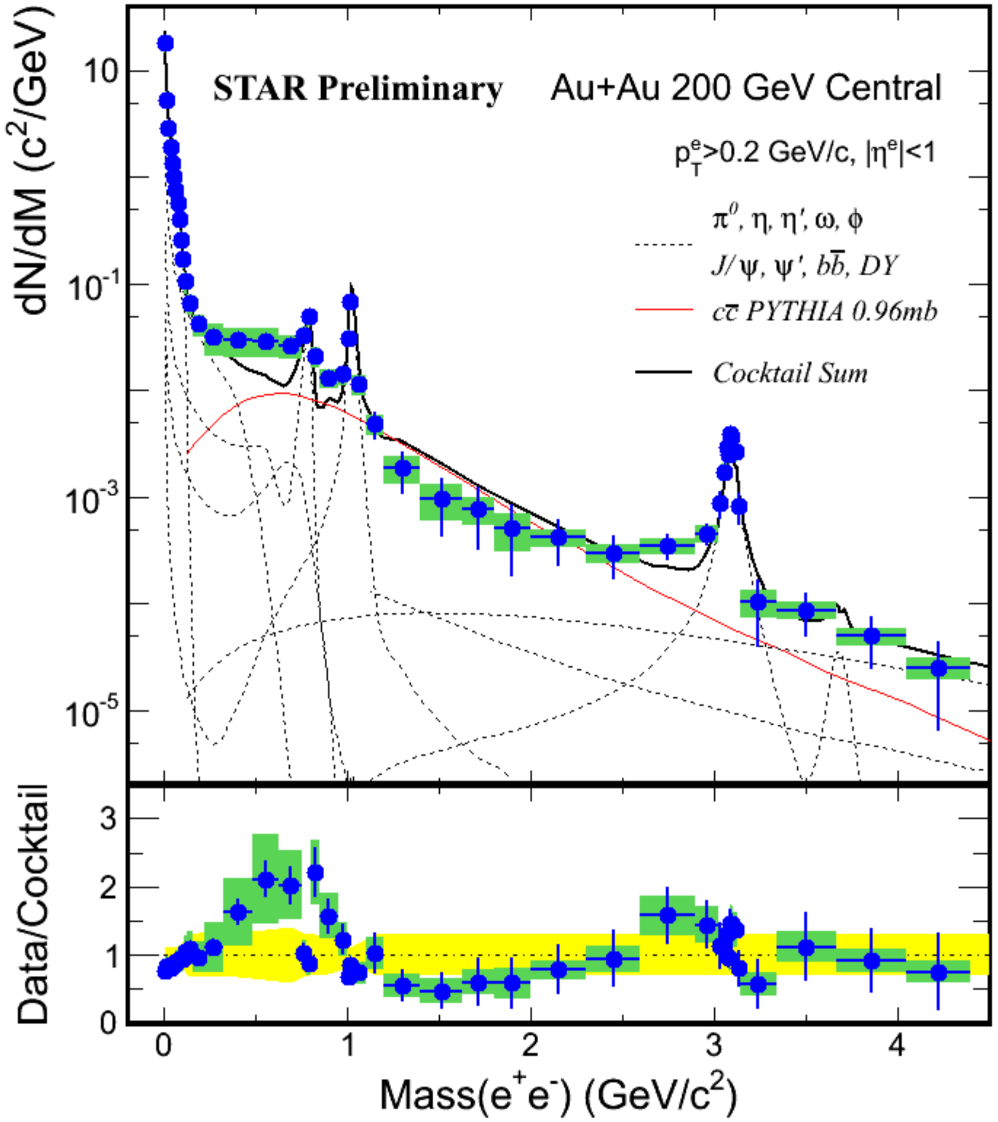
- Low M: HG-dominated
- High-M: QGP dominated

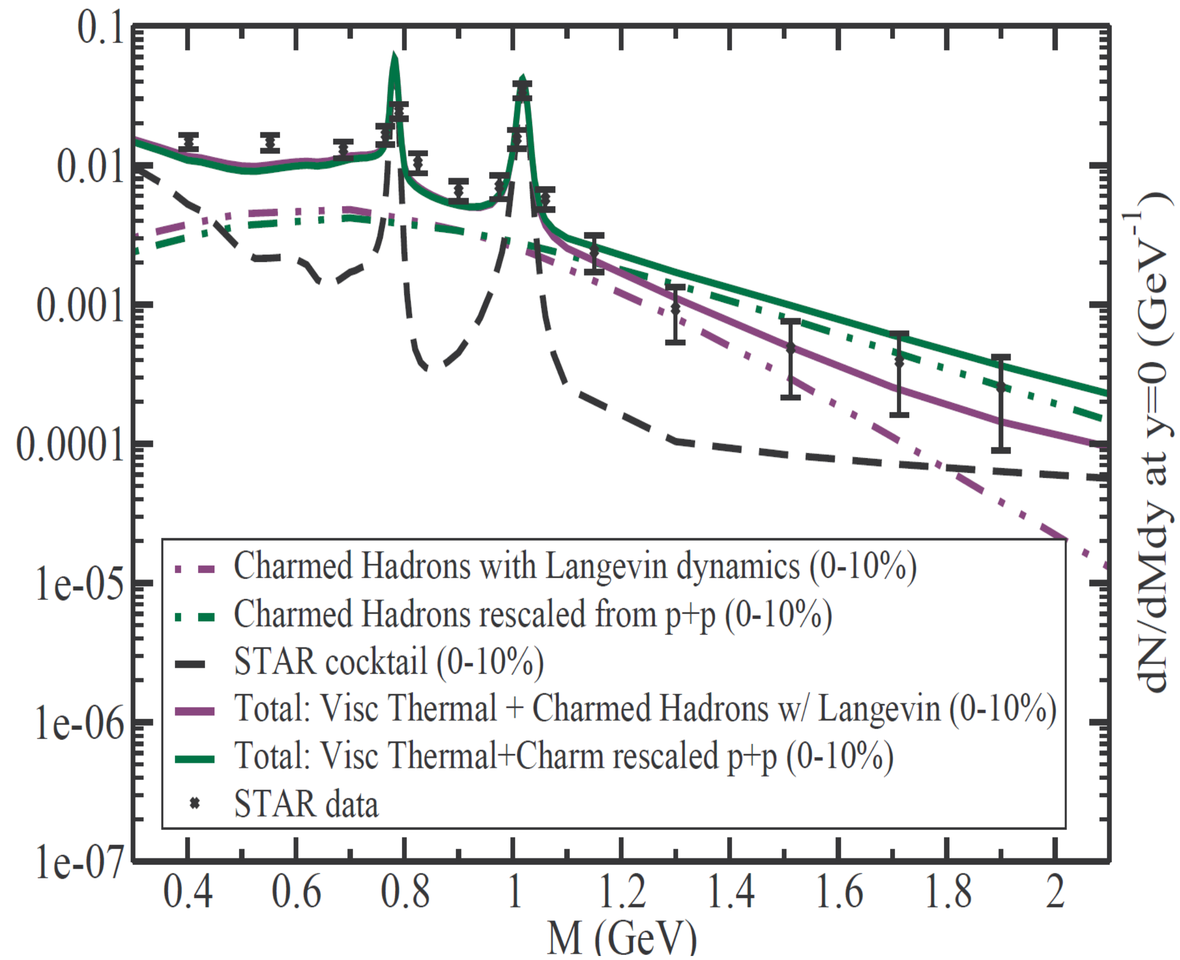
  Chatterjee, Srivastava, Heinz, Gale PRC (2007)

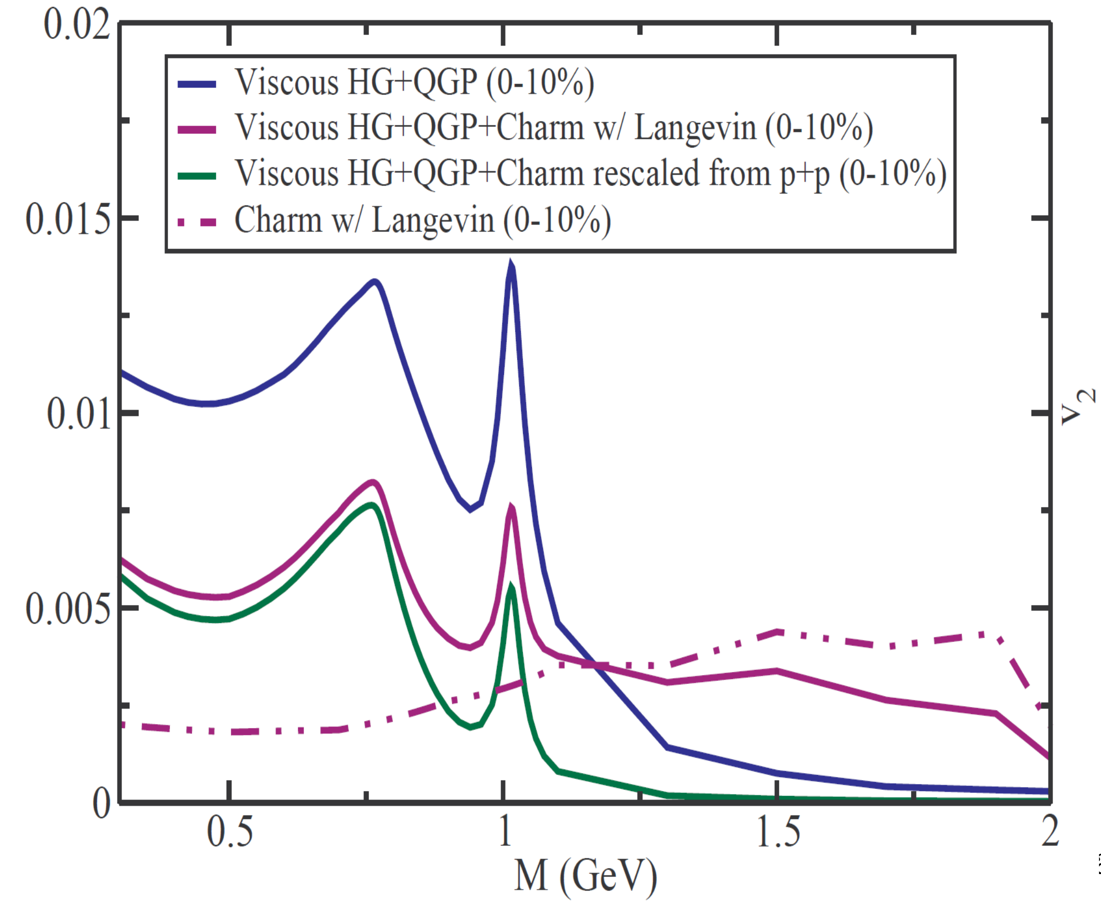
- No open charm here
- v_2 as a function of M will contain some info on the transition regime
- Viscous effects are moderate
- FICs? Coming soon...

G. Vujanovic, 2011-12

Dileptons, some recent results







- Uses MUSIC, and rates compatible with NA60 data
- IMR: sensitive to charm energy loss
  - Clint Young et al., arXiv:1111.0647
- IMR: Thermal effects?
  - Li and Gale, PRL (1998)
- FICs to come

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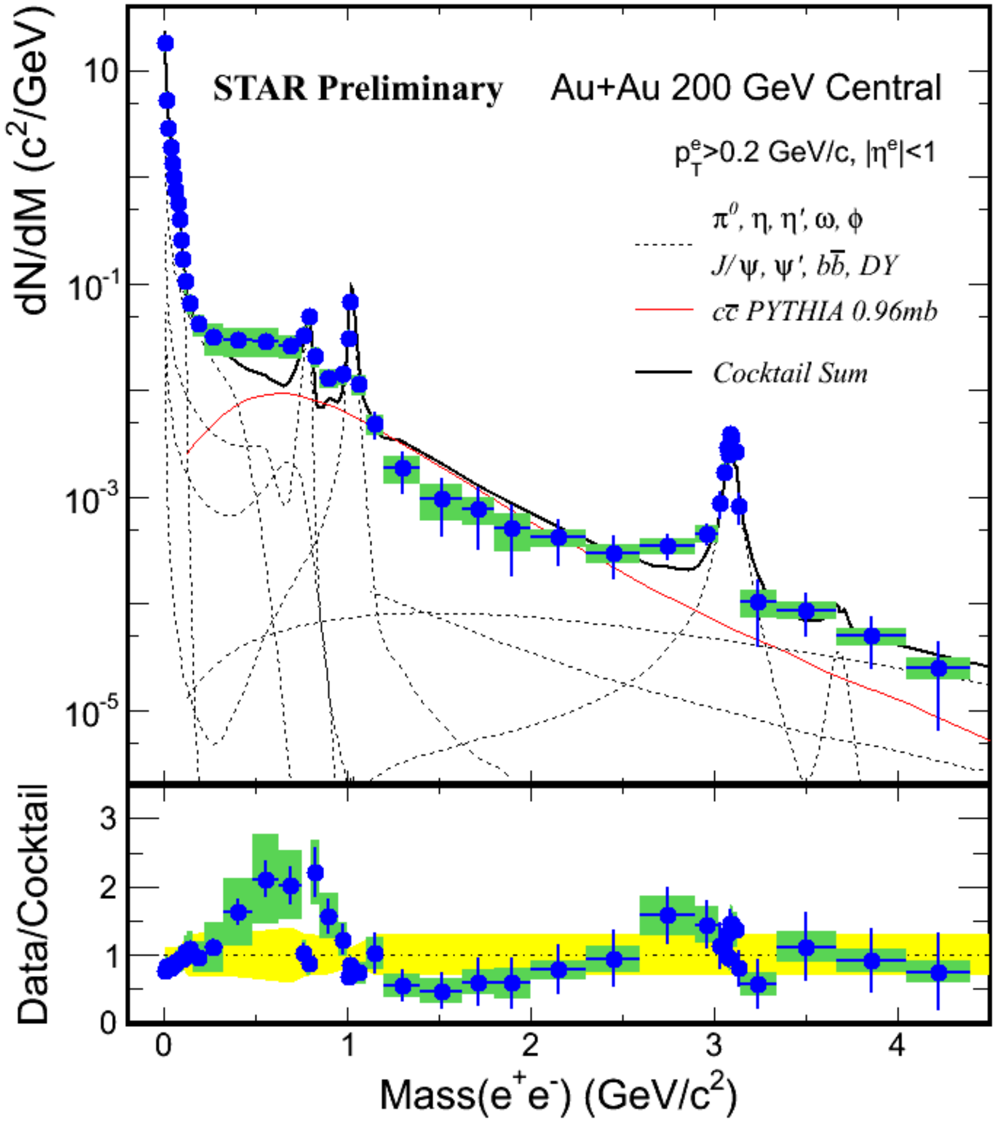

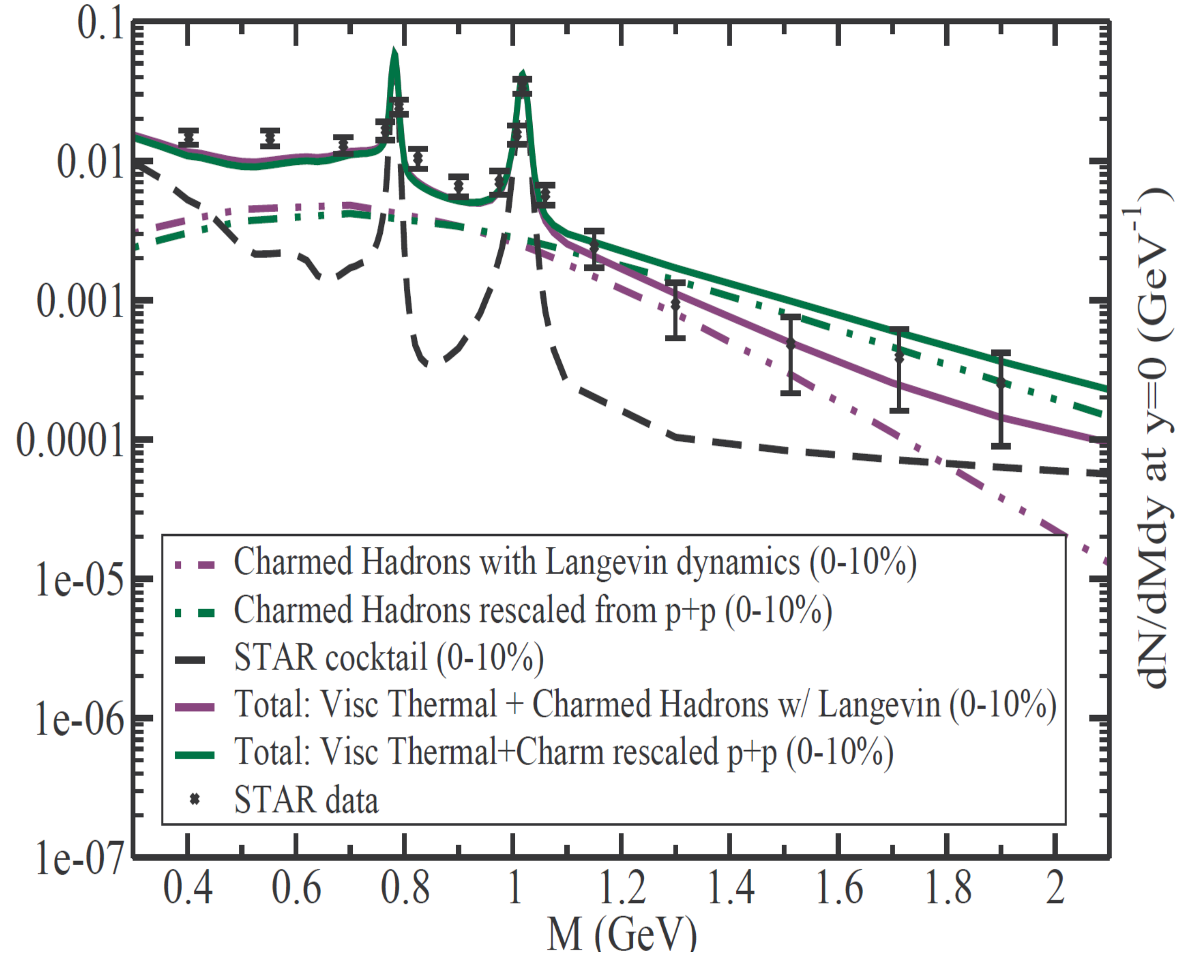

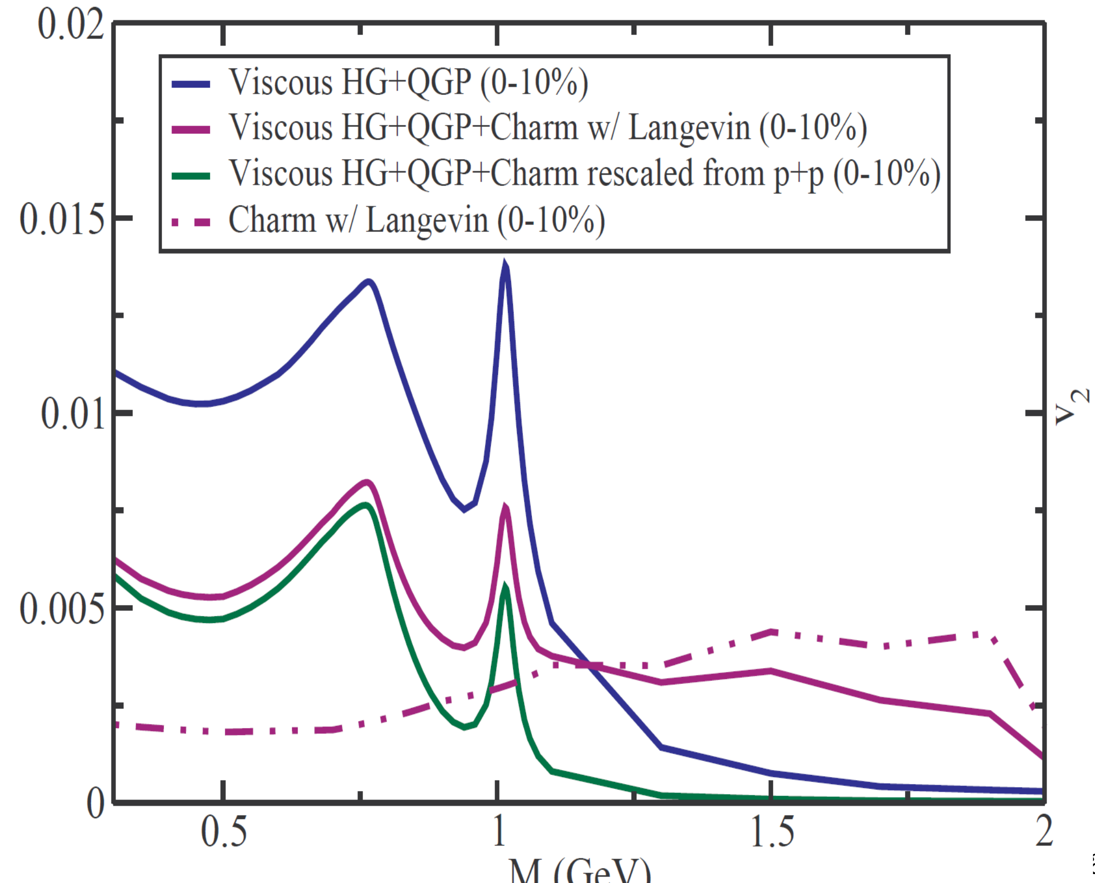

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PROGRESS

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CONCLUSIONS

- The status of EM rates and their integration in dynamical models is still in flux
- Photon v_2 is sensitive to the EOS, and to various hydro parameters such as viscosity, and initial conditions (time and FICs). Current v_2 data is a puzzle. New physics?
- Dilepton v_2 with good statistics is needed to complete the EM emission systematics. STAR & PHENIX?
- FICs and viscosity(ies) make a difference in photon and dilepton characterization: one must be consistent with hadronic data
- Known unknowns: pre-equilibrium radiation, thermal vs. charm components in the dilepton IMR

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Heavy-ion collision theory with momentum-dependent interactions

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(Received 29 October 1986)

We examine the influence of momentum-dependent interactions on the momentum flow in 400 MeV/nucleon heavy ion collisions. Choosing the strength of the momentum dependence to produce an effective mass $m^* = 0.7m$ at the Fermi surface, we find that the characteristics of a stiff equation of state can be obtained with a much softer compressibility.

PHYSICS REPORTS (Review Section of Physics Letters) 160, No. 4 (1988) 189–233. North-Holland, Amsterdam

A GUIDE TO MICROSCOPIC MODELS FOR INTERMEDIATE ENERGY HEAVY ION COLLISIONS

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Received September 1987

VOLUME 35, NUMBER 14 PHYSICAL REVIEW LETTERS 6 OCTOBER 1975

Relativistic Hydrodynamic Theory of Heavy-Ion Collisions*

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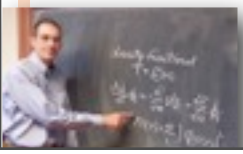
Theoretical Division, Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87544
(Received 11 June 1975)

By use of finite-difference methods we solve the classical relativistic equations of motion for the head-on collision of two heavy nuclei. For ^{16}O projectiles incident onto various targets at laboratory bombarding energies per nucleon ≤ 2.1 GeV, curved shock waves develop. The target and projectile are deformed and compressed into crescents of revolution. This is followed by rarefaction waves and an overall expansion of the matter into a moderately wide distribution of angles.



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Happy Birthday George !